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DoD AND COMMERCIAL ADVANCED WAVEFORM DEVELOPMENTS AND PROGRAMS WITH MULTIPLE NUNN-McCURDY BREACHES

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Preface

This report presents the results of two RAND studies. One compares changes in requirements, technical risk, and cost growth encountered in the development of the key software products produced by the Joint Tactical Radio System (JTRS) network enterprise domain (NED) program with similar elements for the commercial cell phone fourth-generation (4G) long-term evolution (LTE) waveform. The study examines how JTRS networking waveforms' technical and associated program risks were managed, the cost of developing JTRS networking waveforms, and how technical risks and challenging requirements contributed to schedule and cost increases. The objective of this effort was to identify differences between the program management factors and cost structures and investigate the underlying causes of these differences. The second study analyzes programs that have had multiple Nunn-McCurdy breaches (that is, military acquisition programs that have exceeded certain cost thresholds) in an attempt to identify characteristics of programs that overrun their budgets.

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Summary

This report presents the results of two RAND studies: One is a comparative assessment of the capabilities and development approaches used for the Department of Defense (DoD) Joint Tactical Radio System (JTRS) wideband networking waveform (WNW) (a key component of a planned tactical military communications system) and the long-term evolution (LTE) waveform (a key component of advanced commercial mobile communications networks). The second study analyzes acquisition programs with multiple Nunn-McCurdy breaches, that is, military acquisition programs that have exceeded certain cost thresholds.

The first study compares differences in system designs, technical requirements, intellectual property protection schemes, and cost in the development of WNW, one of the key software products produced by the JTRS network enterprise domain¹ (NED) program with similar elements of the commercial cell phone fourth-generation (4G) LTE waveform. The study first examined how the program managed system design, technical risks, and WNW development costs and how technical risks and challenging requirements contributed to schedule and cost increases. These JTRS NED program management factors were then compared to the risk factors, program management approaches, schedule changes, and development costs for the LTE waveform, the most advanced wireless waveform ever developed by commercial industry.

The second study analyzes programs that have had multiple Nunn-McCurdy breaches in an attempt to identify unique characteristics of programs that overrun their budgets.

The main findings and recommendations of both efforts are described below.

JTRS NED Findings and Recommendations

Looking across the issues with the JTRS GMR WNW program that most contribute to its less-than-favorable comparison with LTE, four stand out. First, the amount spent on JTRS Ground Mobile Radio (GMR) and WNW research, development, test, and evaluation (RDT&E) appears to be far less than was needed when compared to the

¹ Essentially a system of systems.

amount spent for RDT&E by commercial firms in the development of LTE. Second, the more evolutionary development approach for LTE along with the higher RDT&E expenditure enabled project personnel to deal with system performance and technology risk issues as they came up. Third, the JTRS program structure that separated hardware and software development coupled with a “big bang” acquisition approach (the delivery of a system that could meet all requirements at Milestone C) not only complicated coordination needs among programs but also may have delayed the discovery of integration problems until it was too late or too near Milestone C. And last, the intellectual property (IP) model used in the DoD JTRS program may have prevented the incorporation of needed technologies into the program that could have reduced technical risks and performance issues. In contrast, the more inclusive Third-Generation Partnership Project (3GPP) IP model encouraged the incorporation of a worldwide and world-class set of technology IP into LTE.

Findings

Organizations and Intellectual Property Rights Differ Substantially

Although the LTE and the JTRS GMR WNW differ significantly in many technical and design aspects, they share some common underlying wireless communications technologies.

The organizational structures that spearheaded the development of these two systems are quite different. Furthermore, the LTE and GMR WNW development approaches and architectures are significantly different. The LTE architecture is not software-defined, but hardware components (microchips in particular) are shared between collaborating vendors. However, software developed by competing commercial vendors is not. IP rights to LTE software are retained by individual vendors in most cases. In comparison, JTRS GMR WNW architecture is software-defined: The software is government-owned and can be shared between vendors, if approved by the government, whereas GMR hardware is not shared outside the original development team of contractors.

The organizational model, and technology-and intellectual property sharing rules differ substantially in the two approaches. The JTRS GMR and WNW products were developed in traditional DoD acquisition programs with IP access controlled by a select number of program contractors and government personnel. IP for executable software code is retained by the government, whereas individual contractors retain IP for hardware designs. GMR and WNW were developed by two acquisition programs, one responsible predominantly for hardware development and for the operating system (OS) software for the hardware platform (the GMR program), and the other (the JTRS NED program) responsible for WNW (a software product). One complication of this arrangement is that a significant amount of coordination was required between the two programs for software development. The JTRS Joint Program Executive Office

(JPEO) was responsible for coordinating and aligning the products of the GMR and NED programs. One mechanism used to effect the coordination of software development efforts was the development of a set of software standards for the JTRS family of radios—the software communications architecture (SCA).

In comparison, the LTE/system architecture evolution (SAE) is specified by a set of technical standards that was developed by the 3GPP international consortium. The consortium's governing body is a global set of regional telecommunications standards-setting organizations. 3GPP also includes industry firms. LTE/SAE standards are developed by industry experts from member firms. Individual firms have the option to offer their own IP to form a part of one or more LTE/SAE standards. If accepted by the group, this IP is then available to other 3GPP members to use in their own products under the terms of the 3GPP essential patent licensing policy. Intellectual property rights (IPR) are retained by the individual 3GPP member firms, but licenses for essential LTE/SAE patents must be made available to other 3GPP member firms on a fair, reasonable, and nondiscriminatory basis.

LTE Had Much Higher Development Costs Than JTRS GMR WNW

One of the most surprising results of this study concerns RDT&E costs. Significantly more funds were expended for the development of LTE than was allocated by the DoD for the development of JTRS GMR WNW. We note that some of the difference may have stemmed from redundant investments by industry competitors, but we tried to take into account this effect in our cost-analysis methodology. LTE RDT&E costs were at least a factor of four greater than those for GMR and WNW and were more likely to be a factor of 10 to 24 times greater.

This finding raises the question as to whether the DoD did not make a large enough research and development (R&D) investment to reduce the substantial technical risks associated with the advanced technologies needed for this program.

Of course, JTRS is not the only DoD program to suffer significant cost growth over the past decade. And perhaps what has been observed with JTRS is just symptomatic of a larger issue within the DoD, where cost-estimation processes lead to overly optimistic and ultimately unrealistic cost estimates for DoD acquisition programs that require the development of advanced technologies.

JTRS GMR WNW and LTE Development Time Lines and Approaches Differ Substantially

The development time lines overall for JTRS GMR WNW and for LTE are comparable. Initial requirements development for the GMR program took approximately six years compared to about five years for LTE. On the other hand, system development took nine years for JTRS GMR and WNW and only six years for LTE. One reason for the significant difference in the latter time line is that there was more concurrent development of requirements and systems in the LTE program.

WNW and LTE share common technologies in radio frequency modulation schemes, but LTE incorporates some advanced technologies not available in WNW such as multiple-input and multiple-output (MIMO) and the use of multiple antennas in handsets and eNode B radio access network nodes. LTE also employs a new, power-efficient, high-performance uplink waveform and wider bandwidth downlink channels than are available in WNW. The LTE network architecture has demonstrated that it is scalable and can support over 1,000 nodes in a single wireless network.

LTE and WNW network and security architectures are substantially different. JTRS WNW is a single-tier, peer-to-peer network where each node is identical and has all the necessary intelligence built into it so that it can function effectively even on the move as part of a mobile ad hoc network (MANET). As field tests have shown, WNW network scalability has not been demonstrated beyond 30 nodes. In contrast, the LTE/SAE network architecture is based on a two-tier network where a single radio access point (eNode B) can support over 1,000 wireless nodes. Finally, both network architectures have yet to fully integrate voice and data communications.

The development approaches for the two initiatives also differ significantly. The JTRS program approach initially called for the development of an entirely new MANET communications architecture that relied on a number of new and unproven technologies. In other words, it used a big bang type of an approach where it was assumed that an entirely new system could be developed and that the new technologies needed to make the system work could be developed concurrently with the system itself. Later, after the program had encountered significant cost, performance, and schedule problems, the program's organizational approach was changed significantly. In the restructured program, hardware and software development was separated into separate programs. It is debatable whether this new organizational approach was a success.

The LTE development approach was decidedly different. As its name suggests, private industry and 3GPP took an evolutionary approach toward development of this new system architecture. LTE represents an incremental development approach for next-generation wireless cellular communications networks. Just as in current 3G wireless networks, voice and data backhaul networks are separated in the initial versions of LTE.² It was judged to be too difficult to integrate them along with all the other architectural changes that were made in the initial versions of the LTE network architecture. In these initial versions, development emphasis was placed on improving the spectral efficiency and performance of the radio access network, on consolidating the number of network nodes needed in the backhaul network, and finally on transitioning the backhaul network to a standard IP-based network. And perhaps most impor-

² The cell towers of wireless mobile communications networks are connected to other cell towers and the core network of the mobile communications provider by means of a backhaul network. The backhaul network may refer to a wire line or fiber optic network, or high-capacity wireless links.

tant, the fundamental two-tiered structure of current wireless cellular networks was preserved in LTE. In this two-tiered structure, the connection between the two LTE network tiers is provided by the eNode B network node, which remains fixed. This is in contrast to the MANET network designs that were developed as part of the JTRS GMR and WNW programs, in which no network nodes have to remain stationary. The evolutionary approach taken in the LTE development enabled the LTE network to scale up to thousands of wireless nodes; in contrast, the MANET network design developed for GMR and WNW was never able to scale up to such large network sizes. The technology needed to do this remains to be developed.

Program Outcomes Were Very Different

It is important to consider the outcomes of these two development efforts. The JTRS GMR WNW development effort lasted for approximately 12 years and has not yet resulted in a product fielded to the U.S. Army. The GMR program was canceled in 2011, and the JTRS program responsible for the development of WNW was restructured in 2012 and is now called the Joint Tactical Networking Center (JTNC). The JTNC will be responsible for the continued development of JTRS waveforms and will assume the responsibility for transitioning these waveforms, including WNW, to commercial radios (radios developed by defense contractors using their own internal R&D funds). So in terms of hardware development efforts, the JTRS GMR program was not a success as it did not lead to fielded hardware products. In contrast, the waveform development part of the JTRS family of programs (JTRS NED) was more successful and has produced advanced networking waveforms that will be used in radios to fielded to U.S. Army and Marine Corps.

Recommendations

Our analysis shows that in hindsight, GMR and WNW development costs do not appear to be exorbitant, given the challenging requirements originally established for the JTRS program, and perhaps the DoD did not invest enough in up-front R&D to reduce WNW technical risks. If WNW is to be scaled up to larger networks of 100 nodes or more, additional RDT&E funds will be necessary. Such an R&D program could be carried out by JNTC or by the Army's Research, Development and Engineering Command, using commercial radios, when they become available.

Another approach will be necessary if the Army and DoD decide that WNW cannot meet future warfighter needs. If this is the case, given the limited R&D dollars likely to be available in future budgets, the DoD should consider adapting LTE to meet its operational and security needs. In this case, a new DoD R&D investment strategy will be needed that leverages best practices from the commercial sector, including the use of technical standards, to foster collaboration among competing defense contractors. Such an approach for the DoD would be new but could take advantage of the model established by 3GPP.

In any case, alternatives to the JTRS development approach based on software-defined radios and waveforms should be considered in future DoD communications systems developments. The JTRS SCA is aging quickly in a world of rapidly changing software architecture standards and may no longer provide the best standards platform for radio development. Furthermore, it is not consistent with recent industry trends toward tighter integration of software and hardware. A technical standards-based approach that also incorporates provisions for licensing essential patents at fair and reasonable prices and in a nondiscriminating fashion should be core tenets of this new R&D strategy.

In addition, alternatives to the standard DoD acquisition process should be sought out for DoD IT and communications system programs. DoD IT and communications should follow the LTE development model and pursue an evolutionary approach. Such an approach is possible if essential patents for current and future (evolved) systems can be licensed in a fair and non-discriminatory basis with competing contractors. DoD should also initiate such programs with a new standards-development phase that enables a broad cross-section of industry to contribute and share patents deemed essential for system development. DoD should also consider altering later program phases to enable broader industry competition that such an IPR-sharing approach will enable.

Finally, the DoD should cast a wider technology net to incorporate the latest commercially developed advanced information technologies. To do this, the DoD should consider joining 3GPP and explore the option of enabling 3GPP common essential patents to be used in military system.

Multiple Breaches Findings

The Performance Assessments and Root Cause Analysis (PARCA) office asked RAND to review programs that had breached Nunn-McCurdy thresholds more than once with the main objective of understanding how these program breaches evolved. PARCA posed the following three research questions:

- Are programs that have a Nunn-McCurdy breach more likely to breach again?
- What can we learn from the cost growth trends of those programs that have had multiple Nunn-McCurdy breaches?
- What can we learn from the management actions taken on programs with multiple breaches? Are there common issues that were missed at the first breach?

At the outset, we note that some repeat Nunn-McCurdy breaches can be attributed in part to changes in legislation rather than new program issues. Furthermore, counting breaches is not as simple as it might appear on the surface. A Nunn-McCurdy breach can either be significant or critical, depending on by how much the program

breaches the threshold.³ For example, does a transition from significant breach to a critical one count as an additional breach? We took as simple an approach as possible. Once a program experiences either an average procurement unit cost (APUC) or a program acquisition unit cost (PAUC) breach, either significant or critical, that constitutes a breach.⁴ We did not consider a program going from significant to critical as an additional breach but rather regarded it as just a further evolution of the same breach. Likewise, we observed generally that APUC and PAUC were so correlated in terms of breaches that counting breaches of APUC and PAUC independently did not make sense. Also, if one or the other lags by a year or so, that would not constitute a second breach. For example, if a program had a critical breach in APUC one fiscal year and critical or significant breach in PAUC the following year, we did not count that as two breaches but rather as a single breach. The only time we restarted the counting is when there was a rebaseline (before 2006) or a recertification. We considered 18 programs with multiple breaches, four in depth.

Our broad conclusions are as follows:

Are Programs with Multiple Breaches More Likely to Breach Again?

Our analysis indicates that programs that breach once are not more likely to breach a second time. The 2006 change in the Nunn-McCurdy law has increased awareness of programs that breach above their initial baselines.

What Can We Learn from the Cost Growth Trends of Those Programs That Have Had Multiple Nunn-McCurdy Breaches?

We found no obvious cost growth trends that would suggest a program might breach more than once.

What Can We Learn from the Management Actions Taken on Programs with Multiple Breaches? Are There Common Issues That Were Missed at the First Breach?

In terms of actions taken at the first breach, those that breach more than once had technical issues that were not resolved by corrective actions taken at the first breach. Finally, we did find some common characteristics among those programs with multiple breaches. But because the sample was small, the results are not definitive, and further research might refine this view.

³ A significant breach occurs if the program exceeds the current baseline estimate by 15 percent or the original baseline estimate by 30 percent; a breach is critical if the program exceeds the current or original baselines by 25 or 50 percent, respectively.

⁴ The methods for calculating the breaches are explained in Appendix A.

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Abbreviations

2G	second generation
3G	third generation
3GPP	Third-Generation Partnership Project
4G	fourth generation
AARW	Army Aviation Rotary Wing
ACAT	acquisition category
A/D	analog to digital
ADM	Acquisition Decision Memorandum
ADNS	Automated Digital Network System
AES	Advanced Encryption Standard
AETC	Air Education and Training Command
AKA	authentication and key agreement
AMF	airborne maritime fixed station
AMP	Avionics Modernization Program
AoA	Analysis of Alternatives
APB	acquisition program baseline
API	application programming interface
APUC	average procurement unit cost
ARG	Amphibious Ready Group
ASR	acquisition stability reserve
ATR	above threshold reprogramming

AUC	authentication center
BCT	brigade combat team
BY	base year
C4	command, control, communications, and computers
CAAP	Common Avionics Architecture Program
CAIG	Cost Analysis Improvement Group
Cdma	Code Division Multiple Access
CMSP	commercial mobile service provider
CORBA	Common Object Request Broker Architecture
COTS	commercial off the shelf
DAB	Defense Acquisition Board
DACA	deployable aerial communications architecture
DAE	Defense Acquisition Executive
DAMIR	Defense Acquisition Management Information Retrieval
DARPA	Defense Advanced Research Projects Agency
DCGS-IC	Distributed Common Ground Station–Intelligence Community
DISA	Defense Information Systems Agency
DoD	Department of Defense
EAC	estimate at completion
EDM	engineering development model
EMD	engineering and manufacturing development
EMU	Engineering Mockup Unit
ENB	enhanced Node B
EPC	evolved packet core
EPLRS	Enhanced Position Location Reporting System
EPS	evolved packet system
ETSI	European Telecommunications Standards Institute

E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EVM	earned value management
EW	electronic warfare
FCC	Federal Communications Commission
FCS	Future Combat System
FMV	full motion video
FUE	first unit equipped
FSS	flight software system
FY	fiscal year
GAO	Government Accountability Office
GEO	geosynchronous earth orbit
GMR	Ground Mobile Radio
GPS	Global Positioning System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GW	gateway
HAIPE	high-assurance Internet protocol encryptor
HEO	highly elliptical orbit
HF	high frequency
HMS	Handheld Manpack Small Form Fit
HSDPA	High-Speed Downlink Protocol Access
HSS	home subscriber server
HW	hardware
IA	information assurance
ICE	independent cost estimate
INFOSEC	information security

IOC	initial operating capability
IP	intellectual property; Internet protocol
IPR	intellectual property rights
IT	information technology
JCTD	Joint Capability Technology Demonstration
JITC	Joint Interoperability Test Command
JPATS	Joint Primary Aircraft Training System
JPEO	Joint Program Executive Office
JROC	Joint Requirements Oversight Council
JSOC	Joint Special Operations Command
JTN	Joint Tactical Network
JTNC	Joint Tactical Networking Center
JTRS	Joint Tactical Radio System
KPP	key performance parameter
L1/L2	Layer 1/Layer 2
LRIP	low-rate initial production
LSTI	LTE/SAE Trial Initiative
LTE	long-term evolution
MANET	mobile ad hoc network
MBITR	Multiband Inter/Intra Team Radio
MCS	Mission Control Station
MDAP	major defense acquisition program
MHAL	modem hardware abstraction layer
MILS	multiple independent levels of security
MIMO	multiple-input and multiple-output
MME	mobility management entity
NAS	nonaccess stratum

NAVAIR	Naval Air Systems Command
NDAA	National Defense Authorization Act
NED	network enterprise domain
NIU	network INFOSEC unit
NSA	National Security Agency
NTDR	Near Term Digital Radio
OEM	original equipment manufacturer
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiplex access
OPEVAL	Operational Evaluation
ORB	object request broker
ORD	Operational Requirements Document
OS	operating system
OSD	Office of the Secretary of Defense
PARCA	Performance Assessments and Root Cause Analysis
PAUC	program acquisition unit cost
PB	President's budget
PC	personal computer
PCRF	policy and charging rules function
PDN	packet data network
PDR	Program Deviation Report
PEO	program executive office
PMB	Program Management Board
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase-shift keying
R&D	research and development

RAN	radio access network
RBS	radio base station
RDT&E	research, development, test, and evaluation
RFP	request for proposal
RRC	radio resource control
RTOS	real-time operating system
SAE	system architecture evolution
SAR	Selected Acquisition Report
SATCOM	satellite communications
SBIRS	Space-Based Infrared System
SBU	sensitive but unclassified
SCA	software communications architecture
SC-FDMA	single-carrier frequency division multiple access
SCP	service cost position
SDD	system development and demonstration
SDO	Standards Development Organization
SDR	software-defined radio
SEC	Securities and Exchange Commission
SECDEF	Secretary of Defense
SFR	System Functional Review
SGW	services gateway
SINCGARS	Single Channel Ground and Airborne Radio System
SIT	system integration test
SRW	soldier radio waveform
SSN	nuclear submarine
SWE/NOR	Sweden/Norway
TACP	Tactical Air Control Party

TCP	transmission control protocol
TIMS	training information management system
TS	top secret
TSPR	Total System Performance Responsibility
UAS	unmanned aircraft system
UE	user equipment
UHF	ultra high frequency
UL/DL	uplink/downlink
UMTS	Universal Mobile Telecommunications Standard
USD (AT&L)	Under Secretary of Defense (Acquisition, Technology, and Logistics)
VHF	very high frequency
VoIP	voice over Internet protocol
WiMAX	Worldwide Interoperability for Microwave Access
WNW	wideband networking waveform
WSARA	Weapon System Acquisition Reform Act

Joint Tactical Radio System

This chapter presents the results of the study examining the Army's JTRS program that uses industry's LTE waveform. It begins with a discussion of the JTRS program background and then describes the objectives of the research. Next, we discuss the analytic approach taken to accomplish the objectives. The following section describes the JTRS architecture, to include a discussion of the JTRS hardware, software, and security architecture. We then summarize the LTE architecture, to include a discussion of the LTE security architecture, software architecture, and description of commercial and DoD deployments. Then we compare the development approaches and organizational structures for JTRS and LTE, and this discussion is followed by a technical performance comparison, to include a comparison of the development time lines associated with both systems. We then focus on development costs for both systems, to include a discussion of the sources and methods used to calculate the associated costs. Finally, we discuss the findings and implications derived from the analysis in this report.

Background of the JTRS Program

On the surface, the DoD's software development efforts in support of the JTRS appear to have been costly and time-consuming and to have led to the development of systems that do not meet their original operational requirements. Such factors have contributed to a Nunn-McCurdy breach for the flagship program of the JTRS family of programs—the Ground Mobile Radio (GMR), and later its cancelation. RAND independently assessed the JTRS GMR program and, used the results of this assessment in this analysis.¹

JTRS is a family of radios and a family of communications waveforms designed to be interoperable and provide U.S. military forces with next-generation systems for digital voice and data communications during military operations. Interoperability for JTRS has two dimensions. First, two JTRS radios using the same waveform are

¹ The results of the RAND independent assessment of the JTRS GMR program are not available to the general public.

designed to exchange information effectively. Second, JTRS software-defined waveforms developed originally on one JTRS hardware platform or radio are designed to be portable and to function effectively on a different JTRS radio. The transfer of a waveform from one hardware platform to another is called waveform porting. JTRS waveform porting is theoretically made possible through the use of a software communications architecture (SCA) that provides a common software “operating system” (OS) for JTRS radios, much like Microsoft Windows provides a common operating system for personal computers developed by different manufacturers.

The above discussion indicates that key software development items are JTRS waveforms. A waveform provides the key wireless communications functionality that defines how information is encoded on the radio frequency emissions of the radio. But in the JTRS program, waveform has a broader meaning and definition because it includes the entire set of protocols and standards that are used to manage the wireless network and to encode information as Internet protocol (IP) packets used by the radio itself. During the development of the JTRS radios, in particular the development of the GMR and the wideband networking waveform (WNW)—the most ambitious and complex waveform developed in the entire program—it became clear that development of these key software components took longer and was more difficult than originally anticipated. This led to schedule delays that affected the JTRS GMR program.

Objectives of the Research

The history of the JTRS program raises several questions: How do commercial industry development processes differ from those used in the JTRS program? Does commercial industry produce radios and associated software more effectively and efficiently than the DoD? Can the DoD learn from commercial industry better ways to develop wireless communications systems that could be applied to future DoD programs?

The objective of our effort is to determine whether DoD software development and related acquisition processes are more costly and time-consuming than commercial approaches. We compare the development approaches for the JTRS WNW to those of a similar commercial waveform. The commercial waveform selected for comparison was the 4G cellular telephone communications system that uses the LTE waveform. We selected LTE because it is the most advanced waveform developed to date by commercial industry for wireless cellular communications and is being widely adopted around the world for next-generation 4G cellular networks. JTRS WNW is the most advanced wireless communication waveform developed by the DoD for terrestrial communications.

Analytical Approach

As part of our effort, we compare WNW and LTE performance requirements, their associated system architectures, development time lines, technical complexity, technical risks, organizational structures, and associated costs. Given that LTE network nodes (radio terminals and handsets) are not software-defined and that vendor-specific implementations of the LTE waveforms are not hardware-independent, this effort compares associated hardware and software research and development (R&D) costs and capabilities for both LTE and WNW (e.g., the JTRS GMR).

Originally, we focused only on comparing the cost of developing the waveforms. However, as we analyzed the LTE development process and system architecture, we determined that it did not make sense to compare only the development process for waveforms because of the tight integration between hardware and software that characterizes the commercial radio development process. For this reason, we decided to include the hardware development process as well as the software development process in our analysis.

Development approaches for DoD systems and commercial systems differ in several ways. For JTRS, it is easy to separate the hardware from the software in the development model. In fact, the development model is designed to enable a complete separation of those products so that different vendors can deliver them.

The commercial world takes a completely different approach. Its approach is based on establishing standards for key functionality of the wireless communications device and network. It also has been structured to enable competing firms to offer intellectual property and patents to a larger consortium of developers. The consortium can then decide how intellectual property is incorporated into the standards that define the wireless communication system. The product of this cooperative development process is not hardware or software but rather standards.

Previous RAND studies that examined the JTRS program in great detail informed our analysis of the JTRS program. RAND has been active in the analysis of the technical capabilities and limitations of JTRS radios for the Assistant Secretary of Defense for Research and Engineering and also for the U.S. Army. In these efforts, RAND examined how JTRS radios can be used to build large complex networks to support Army brigades.² We relied on that information and our knowledge of the JTRS program to develop a description of how the JTRS family of programs under the JTRS Joint Program Executive Office (JPEO) developed waveforms and associated hardware. We also used DoD Selected Acquisition Reports (SARs) to estimate the cost of development of JTRS hardware and software.

A separate and different analytical approach was necessary to analyze LTE. Several resources are accessible on the Internet regarding the LTE development process

² The results of these RAND analyses are not available to the general public.

because it is conducted by an international consortium, the Third-Generation Partnership Project (3GPP).³ In addition, we took advantage of contacts RAND had established with key LTE industry firms. We used these contacts to identify knowledgeable engineers in LTE firms who were familiar with the LTE development process and with the 3GPP consortium. We interviewed several individuals in industry who have played a key role in the development of the LTE waveform. During these interviews, we were able to corroborate, understand, and establish a more detailed description of the development processes for the LTE waveform. We provide details below on the organizational structure of both the JTRS program and LTE.

The analytical approach used for the JTRS cost analysis consisted of combining DoD research, development, test, and evaluation (RDT&E) cost estimates for software (WNW/soldier radio wavefore [SRW]) and hardware (GMR). Although ideal cost comparisons would isolate hardware and software development and program management costs, the original iteration of the JTRS program integrated both the hardware and waveforms into one program to facilitate management of program interdependencies. Available data provide only a rough cost division of both efforts. Further, the restructure in 2006 that separated both programs possibly shifted faults of WNW development into GMR costs through unit reductions. Thus, the most accurate cost for the development of the JTRS WNW capability is obtained by combining the software and hardware estimates.

The cost analysis approach for LTE was significantly different because this type of information is not readily accessible because of the number of U.S. and international firms that have been involved in the development process. Because of uncertainties regarding some of the data available, a number of different cost analysis approaches were used to develop a range of cost estimates for LTE. The details of these different cost analysis approaches are described later in this report.

We used publicly available information from 3GPP, including their published time lines for the development of LTE and related networking standards, and interviews with engineers at key firms that participated in the development of LTE standards and in the development and manufacturing of LTE-related equipment. We also made use of data that can be found in LTE standards and related performance requirements.

From the start of this research, we were aware that the LTE and WNW waveforms were developed to support different mobile network operational goals. In this study, we do not wish to leave the impression that these two systems are equivalent. They are not. They share some common underlying technologies and have some common attributes, but the two architectures were developed for two very different sets of operational requirements, or in the parlance used in the commercial world, two very different business cases. Below, we describe these architectures and the differences in operational requirements. Despite these differences, it is instructive to examine whether the two

³ See 3GPP, "The Mobile Broadband Standard," website, undated.

architectures were developed using similar or different acquisition processes and the cost of these developments using these acquisition approaches. The majority of this report is devoted to these questions.

A separate question, which we entertain briefly at the conclusion of this report, is whether the LTE architecture and some of its essential technological components can be adapted to provide mobile communications to military tactical users. Such an adaptation may require significant changes to LTE equipment and architecture. Although the full answer to this question is beyond the scope of the current effort, we believe that it may be possible to satisfy a high proportion of GMR and WNW requirements but certainly not all of the operational requirements originally levied on the JTRS development programs.

Analytical Limitations

Our analysis was subject to certain limitations because it was conducted at an unclassified level and did not include a full examination of all of the features of proprietary LTE waveform implementations. Vendor-specific implementations of LTE may not perform at the maximum levels (e.g., in terms of data rates) specified in the 3GPP standard. Only test results could reveal such flaws, and such test data were *not* examined in this study. However, an informal review of published commercial carrier LTE test results reveals that vendors are able to produce equipment that can meet the full capabilities of the LTE waveform specified in Releases 8 and 9 of the LTE standard. In addition, because of the limitations mentioned above, a detailed comparison of the security features of the two different networking systems was not possible. We also did not attempt to identify all possible vulnerabilities associated with the two network architectures. Such an investigation is beyond the scope of the current study. However, our experience with several other commercial and DoD communication systems leads us to feel that it is plausible to assume that the LTE architecture contains more vulnerabilities and has more security issues associated with it than GMR and WNW. Although GMR never received a full and complete information assurance (IA) accreditation by the National Security Agency (NSA), the JTRS program office took many of the steps needed to obtain such accreditation.

In addition, it is well known that the LTE waveform is not designed to be jam resistant. It is designed to operate in a benign environment where other users of the frequency spectrum will not violate the Federal Communications Commission (FCC) spectrum allocation rules. On the other hand, GMR and WNW have the provision to operate in a contested electronic warfare (EW) environment. These additional military features are unique to GMR and WNW. Full analysis of these issues would require a classified study; however, we can surmise at the unclassified level that GMR and WNW do have additional capabilities that are not present in the LTE waveform.

It is relatively straightforward to estimate the R&D costs for GMR and WNW developments. However, as described above, we found it more difficult to estimate the costs of R&D activities for LTE, because R&D budgets for particular products are typically treated as proprietary information inside private firms. However, publicly listed firms do provide an exact accounting of their total R&D spending in their corporate fiscal year. We used this information to estimate LTE R&D costs. We also had to use other data, including patent information, to provide such estimates. The cost analysis section of this report provides a detailed description of all the parameters used in developing these cost estimates. We wish to point out that because we did not have direct access to detailed corporate financial records, there are some limitations in our cost analysis. Because of this, we use several different analytical techniques to estimate these costs.

Architecture

The original concept for the JTRS program dates to 1997 and was born out of the need to make DoD radios interoperable. Earlier DoD radios, especially those used by the different military services, were not interoperable except in very limited ways. To address this shortcoming, planners and technology experts in the DoD had envisioned an entirely new development approach to deliver interoperable radios that could be used by all military services. Because JTRS was to incorporate the wireless communications requirements of all four services, it took some time to establish joint requirements for the program. In 2001, JTRS requirements were established and the program began with a Milestone B decision in 2002. However, the program development was not smooth and the program was restructured several times during the first five years of development. Initially, the program began as five separate radio programs (termed the JTRS Cluster programs) that would be managed by a single program executive office (PEO). This program structure was later changed, and JTRS hardware and software development activities were placed into separate programs. We will describe below how this restructuring occurred and how the program offices were changed.

We will also discuss the JTRS architecture as it evolved from the beginning of the program and as it was later defined in the 2008–2009 time frame after the major restructuring referred to above was completed. In this study, we will focus on only a few key parts of the overall JTRS family of programs: GMR and WNW.

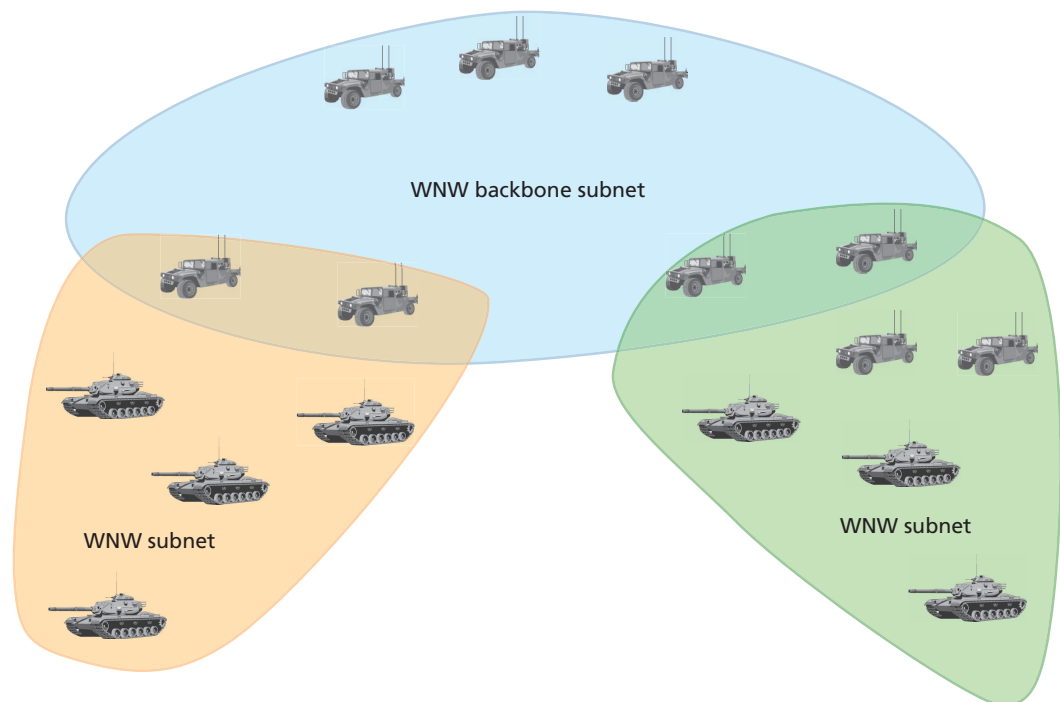
The GMR program was responsible for the development of the hardware required for the GMR device. The JTRS NED program was responsible for all waveforms developed in the JTRS family of programs and, in particular, for the waveforms that would run on GMR. The most complex and capable waveform in the JTRS family is WNW. Because of its complexity, WNW requires substantial hardware resources (processing power and memory) to run effectively. When it was originally developed, only the

GMR prototype radio could run WNW. Together, GMR and WNW can substantiate a JTRS WNW network.

JTRS WNW provides a peer-to-peer, wireless MANET where all nodes are the same and no master nodes or base stations are required. The lack of a master node in the network is desired because even if one or more nodes on the battlefield are damaged or destroyed, the network will continue to operate effectively.

Figure 1.1 illustrates a JTRS WNW network with several subnets that operate at different frequencies. WNW is designed to provide wireless digital IP-based communications. Although no firm requirement was ever established for the required minimum size of the WNW network, the WNW MANET was a key part of the network in the Army's original plans for the Future Combat System (FCS). The FCS force design relied on relatively light armored vehicles, new high-technology sensors, communications systems, and weapons. FCS vehicles were designed to be light, so that they could be airlifted by C-130 transport aircraft. FCS-equipped units would be survivable because they were envisioned to be capable of finding and striking enemy targets faster and from longer ranges than adversary forces could. A robust communications network was necessary to enable this bold new "net centric" operational concept. For these reasons, the FCS and JTRS programs were linked. FCS force designers assumed

Figure 1.1
JTRS WNW Network



that a large number of JTRS GMR equipped nodes, running WNW, would be linked into a high-capacity, low-latency network in an FCS-equipped brigade. This network would include JTRS nodes running WNW and SRW and a smaller number of combat vehicles equipped with satellite communications capability. In other words, WNW was a key ingredient in a network of networks that was to include over 1,500 nodes. As stated by the GAO, “For example, current plans call for the network supporting a BCT to include more than 5,000 nodes on over 1,500 radio sets running at least four different advanced networking waveforms. . . .”⁴

Later, after the FCS program was canceled, the Army developed plans to use GMR and WNW as a core part of the tactical network of Army maneuver brigade combat teams (BCTs). These brigades were envisioned to have over a 100 or so WNW-capable nodes, a number that corresponded to the number of key leader or command positions in a maneuver BCT.

JTRS WNW networks were designed to remain robust even when a large fraction of these vehicles were on the move. This capability was needed so that the network would remain functional even when JTRS-equipped vehicles moved over difficult terrain. In this case, WNW would adapt to the changing network topology or connectivity of the WNW network without suffering a degradation in network performance. GMR nodes would still be capable of transmitting information across the network regardless of how frequently the network topology changed because line-of-sight radio connectivity between vehicles was obscured. Another key aspect of the network design is that the network would remain effective even as the number of vehicles or radio nodes in the network increased. This latter capability is called mobile ad hoc network (MANET) scalability. However, as mentioned above, no firm requirement for MANET scalability was established in the original JTRS Operational Requirements Document (ORD).

It is important to note that most “legacy” tactical radios used by the Army and Marine Corps over the last decade provide data communications networks that are relatively static in terms of their network design or topology. Such legacy tactical radios also have a limit as to how many radios or nodes can participate in a single wireless network. What was new and more demanding technically than WNW was to provide network scalability and the ability of the network to adapt and change as network connectivity changes and simultaneously to provide the same network capacity or data rates to individual GMR radio nodes. It turns out that providing these new MANET capabilities has proven much more difficult to do than originally envisioned.

⁴ Government Accountability Office, “U.S. GAO—Defense Acquisitions: Significant Challenges Ahead in Developing and Demonstrating Future Combat System’s Network and Software,” Washington, D.C., 2008.

JTRS Hardware

Another key requirement for GMR that proved to be more difficult to achieve than originally envisioned was to provide a radio that could fit within the limited space available in many legacy combat vehicles and that could be powered by the power systems of the vehicles.

One reason why the GMR radio is so large relative to legacy tactical radios is that it would provide four independent communication channels with one of these channels operating at high power (100 W). This capability requires high-power amplifiers to support both WNW and the SRW. SRW is a waveform that shares many of the same characteristics as WNW but is not designed to provide as high a capacity as WNW or operate at the same high-power levels. SRW is designed to operate on smaller radios, including handheld radios that could be used by individual soldiers and at shorter ranges.

The final proposed version of GMR hardware is shown in Figure 1.2. Pre-engineering development model (EDM) GMR platforms are significantly less capable. The universal transceivers shown in the figure create the wireless waveform for each channel. The network INFOSEC unit (NIU) also shown contains an NSA-approved encryption device that encrypts and decrypts communications packets for each channel and that can also route packets between channels and to the external interfaces of the radio, which can be connected to various command and control devices in the vehicle. The display device is used to set up and configure GMR and WNW networks.

Figure 1.2
JTRS GMR Hardware



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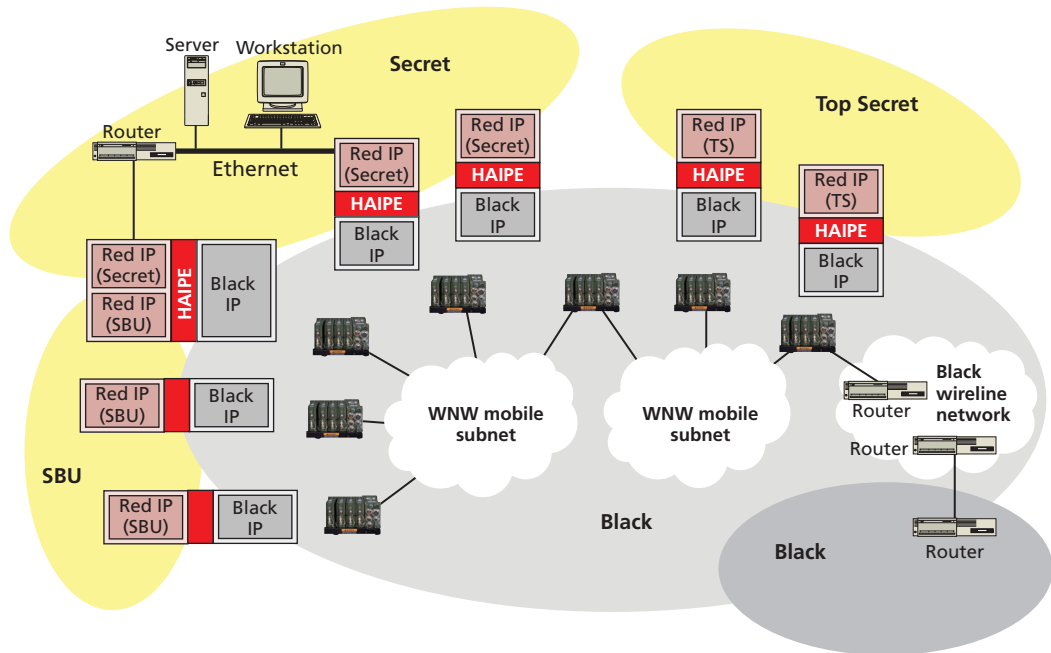
One additional challenging aspect of GMR was the requirement that it be able to operate over a wide spectrum band and support communication channels in high frequency (HF), very high frequency (VHF), and ultra high frequency (UHF), L-band (25 MHz to 2 GHz). This requires including a number of different power amplifiers in the system that can operate in these different bands and isolating them effectively from one another to prevent electromagnetic interference.

JTRS Security Architecture

A key aspect of the JTRS WNW network is the security architecture it would support. This is also a key area that differs significantly from what would be available in a commercial wireless communication system. Interviews with program officers in the JTRS program and reviews of program documentation indicate that the development of the JTRS security architecture was difficult and caused some program delays and may have been the source of some program cost increases.

WNW security architecture supports multiple independent levels of security (MILS). This enables external devices and data sources that operate at different security levels to use the same JTRS WNW network, as shown in Figure 1.3. IP packets

Figure 1.3
JTRS WNW Network Security Architecture



SOURCE: Adapted from "Joint Tactical Radio System Update: Tactical Networking," Free Online Library, undated.
RAND MG1171/5-1.3

transmitted between nodes in the WNW network would be encrypted at the source node and decrypted at the destination node(s). Nodes that relay the packets between source and destination would not decrypt the IP packets. This makes it possible to restrict possession of the cryptographic keys essential to reading the message to only the recipient and transmitting nodes. Such a network is called a “black core” or “colorless core” network so that even if an adversary were able to eavesdrop on a WNW network and extract IP packets from the data stream, it would not be able to interpret the message unless it could also decrypt the packets. The encryption device that enables such a black core network to be formed is the NSA-approved, high-assurance Internet protocol packet encryptor (HAIPE).

The figure shows that HAIPE can support the simultaneous and independent transmission of IP packets from secret, top secret, and sensitive but unclassified (SBU) network enclaves. Devices in these network enclaves could all share the same JTRS WNW transport layer. This is made possible by encrypting information at the packet level. In the figure, Black IP signifies an IP network in which IP packet payloads are encrypted. Only the packet headers remain in plain text. The HAIPE device in each GMR can decrypt Black IP packets with the encryption key appropriate for the classification level of the message and network node destination and convert them to plain text (Red IP packets). The advantage of this type of security architecture is that it can support three network enclaves operating at different security levels with only one transport network. Absent such a capability, three separate transport networks would be required with three separate encryption devices.

The GMR and WNW security architecture is a unique capability of these military systems and provides some unique advantages for securing military communications. Although it was difficult to accomplish, the GMR program eventually did succeed in obtaining GMR and WNW NSA information assurance certification for these systems. There is no equivalent capability or analog available in the LTE architecture. The latter architecture would have to be modified.

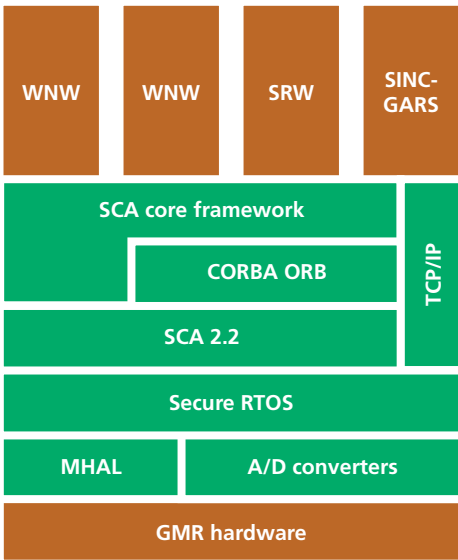
JTRS GMR Software Architecture

As mentioned above, after the JTRS family of programs was restructured, software and hardware development activities were segregated into separate programs. GMR is an example of a software-defined radio (SDR). In such a radio system, it is possible to change the software running on the radio without changing the hardware. In this way, it is theoretically possible to upgrade the software in the radio, and possibly its performance, without upgrading the hardware. In addition, it was also thought that this would be a way in which waveforms developed by particular vendors could be loaded and used on radios developed by other vendors. In other words, an SDR approach would enable more competition and possibly lower cost for military radios. However, the last statement must be considered as only a hypothesis at this point because evidence of effective competition in JTRS radios is yet to emerge.

The GMR software architecture is designed to conform to the JTRS software architecture, which all JTRS radios comply with. The basis for this architecture is the SCA, which provides a framework and application programming interfaces (APIs) that enable higher-level software components (e.g., waveforms such as WNW and SRW) to be separated from the hardware components of the radio. Shown in Figure 1.4 are some of the key software components of the JTRS GMR software architecture.

In the figure, waveforms are indicated by the brown rectangles at the top of the software stack. These use the waveform interface and other radio services shown in the middleware and hardware building blocks below. The software components shown in green constitute the middleware and operating system of the SDR. GMR was based on a specialized version of the Linux operating system. This operating system was specially configured and “locked down” to conform to the security requirements for the JTRS program and also in an attempt to ensure that the radio could perform all necessary information processing functions in real time. What we mean by this is that information that was to be transmitted by the radio would be ready in memory for retrieval by the waveform so that it could be transmitted as a wireless signal at the required data rate.

Figure 1.4
JTRS GMR and WNW Software
Architecture



SOURCE: Adapted from Douglas C. Schmidt, “Open System Architecture (OSA): Challenges & Success Drivers,” Vanderbilt University, Defense News Open Architecture Summit, October 18, 2012.

RAND MG1171/5-1.4

As alluded to above, another important requirement for the software architecture is that it could be used by multiple vendors and waveform developers. Consequently, the top-level APIs used in the architecture are defined in a common industry format, which, although it was developed for other purposes, was adapted for use in SDRs.

Consequently, the SCA core framework depends on the real-time object request broker (ORB) of the CORBA framework, which makes systems calls to the underlying real-time operating system (RTOS). The use of the CORBA framework provides an interoperability framework and standardization for developers. However, its use in the SCA has been criticized by some experts because it relies on high-level programming language software artifacts. The use of CORBA in a radio requires complex compilers and command translation. This can reduce performance and increase time delays for complex CORBA transactions. In this regard, it should be noted that this type of software development approach has not been adopted in LTE. Instead, commercial developers of LTE systems and components use their own proprietary software development frameworks and maintain intellectual ownership of the software embedded in their systems.

Another challenge in the development of the GMR and WNW software architecture is actually connecting it efficiently with radio hardware. This is done through two types of components shown in Figure 1.4: the modem hardware abstraction layer (MHAL) and the analog-to-digital (A/D) converters. At some point, waveform data have to be converted into analog radio signals. This is done by the MHAL and A/D converters. And the reverse has to be done for incoming waveform radio signals. This is also done by the same baseband components: the MHAL and A/D converters. This entire architecture requires 2.4 million lines of software code in addition to the million lines of code already embedded in the Linux OS.⁵

Long-Term Evolution Architecture

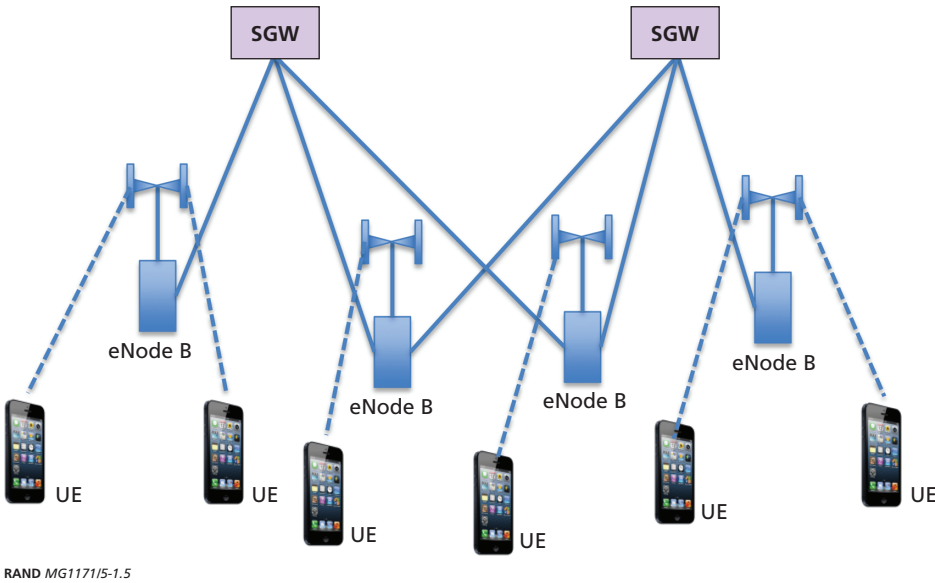
Commercial cell phone networks have evolved rapidly from their start in the early 1980s. The networks have been upgraded by commercial mobile service providers in a series of major releases or network generations. The latest and most advanced cell phone network is referred to as the 4G network or LTE, which is not a peer-to-peer network as is WNW; in contrast, it has two scalable network tiers.

eNode B

Users with wireless mobile devices connect to the radio access network (RAN) through enhanced Node Bs (eNode Bs) wireless network access points. As shown in Figure 1.5,

⁵ A complete description of the JTRS GMR and WNW software architecture is beyond the scope and classification of this report.

Figure 1.5
LTE Wireless Cellular Communications Architecture



the wireless connection between user equipment (UE), which in many cases will be cell phones, and the eNode B is indicated by the dashed lines in the figure.

Figure 1.5 shows the LTE RAN and initial services gateway (SGW) entry points into the core LTE communications architecture. The central node of the RAN is the eNode B, which is typically equipped with antennas mounted on cell towers or buildings. User equipment connects to the eNode B using the wireless channel that is often referred to as the LTE waveform (we describe the features of the LTE waveform below). eNode Bs are connected into the LTE backhaul network through SGWs by means of fiber optic links or high-capacity, point-to-point, wireless links as shown in the figure.

The LTE waveform provides substantial improvements in end-user communications capacity on both the uplink and downlink to the eNode B and increased cell tower sector capacity and promises to reduce messaging latency. LTE supports Internet protocol-based traffic with end-to-end quality of service (QoS) features. The first deployed version of LTE, Release 8, which became available in 2011, provides data services only. Later versions of LTE will provide integrated voice and data services. When LTE voice becomes available, voice traffic can be provided using several implementation options. One of these will be voice over Internet protocol (VoIP).

It is interesting to note that commercial telecommunications carriers have not yet deployed an integrated voice and data LTE network. It has taken longer than originally anticipated for LTE developers to perfect such a solution, but commercial industry is still working on one. Some industry observers have stated that such a solution will be available in Release 10 of LTE. At one point, VoIP was envisioned for voice com-

munications using WNW on the JTRS GMR, but this possibility now seems remote because of the limited communications capacity available in WNW networks with mobile nodes.

Figure 1.6 illustrates the rack-mounted equipment for a radio base station (RBS) 6201 LTE eNode B, the base station produced by Motorola. Not shown are the antennas that would also be a part of the system. Smaller, more compact eNode B terminals that are less than one-quarter the size of the terminal shown in the figure are now available. The eNode B is the central hub of the wireless portion of the LTE network. It manages all wireless network connections to user equipment and has the capacity to control up to 200 users per cell in 5 MHz of spectrum. So if a single eNode B has access to 20 MHz of spectrum, it can manage up to 800 users per cell. In addition, if the eNode B employs sector antennas and provides three independent sectors, each using an independent 20 MHz block of spectrum, it would be able to support up to 2,400 users.

It is interesting to compare the sizes of the wireless networks that can be supported by LTE and JTRS WNW. Although WNW was originally designed to support networks with as many as 200 nodes, it has been demonstrated to work effectively only

Figure 1.6
LTE Base Station



SOURCE: Motorola, "Long Term Evolution (LTE): A Technical Overview," Technical White Paper, 2007.

RAND MG1171/5-1.6

with networks with a maximum of 30 nodes (as of 2012). In contrast, the LTE RAN can easily support network sizes of over 2,000 nodes. LTE does this by employing directional or sector antennas and using wide 20 MHz spectrum blocks. Nevertheless, one can see that an LTE network at the radio access layer can scale up to many more users or nodes than WNW.

When comparing LTE RAN equipment to JTRS GMR hardware, it is appropriate to consider both the end-user device (mobile phone) and the eNode B terminal. On one hand, LTE end-user devices are much smaller than GMR terminals. On the other hand, a typical eNode B base station, as indicated in Figure 1.6, may be several times larger than a complete suite of GMR equipment. Partly because the JTRS WNW network is a peer-to-peer network, all nodes are of equal size, whereas in an LTE network, the functional capability of end-user devices and eNode B terminals is significantly different and so are their sizes, their power levels, etc. Network control functions are all housed in the eNode B terminal. In contrast, the end-user equipment or mobile phone has much less intelligence built into it and is designed to provide the end user with applications and middleware to support user interface and information display functions.

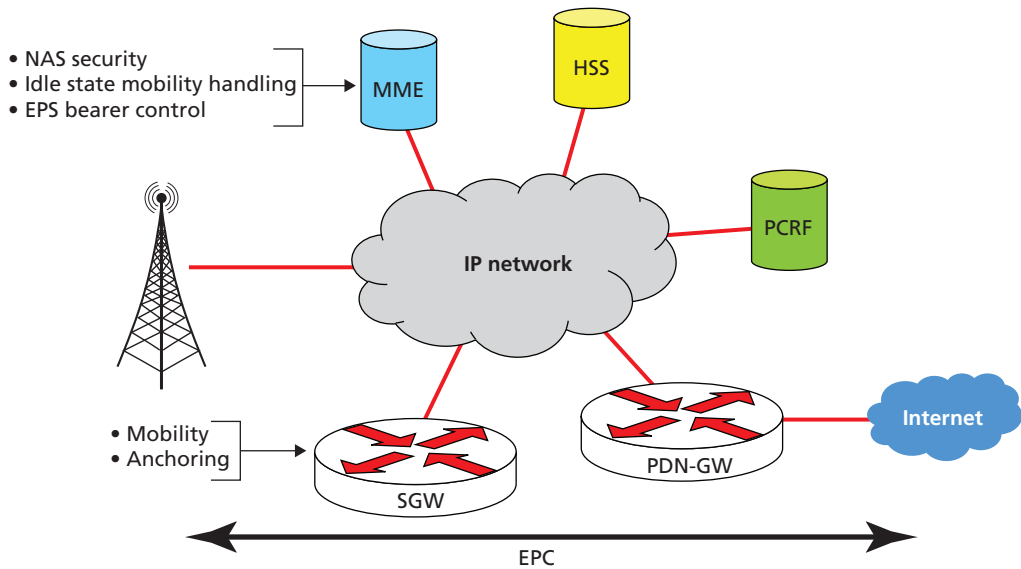
LTE Evolved Packet System

The LTE communications architecture is based on a set of standards that was developed by an international organization called 3GPP. Below, we describe how this organization functions and how it led to the development of LTE. In developing LTE, the 3GPP specified a new packet core, the evolved packet core (EPC) network architecture. The EPC architecture is simpler than the third-generation (3G) core network design and has fewer network elements, with simpler functionality, improved redundancy, and improved interoperability, which allows for connections and handover to networks using other fixed line and wireless access technologies.

An overview of the LTE system architecture evolution (SAE) network architecture is shown in Figure 1.7. For the sake of brevity, we do not delve into all the details of LTE networks. Instead, we provide an overview of LTE networks and describe the key network nodes and functions they perform. Note that user equipment is not shown in the figure. A voice or data call is started by user equipment that establishes a wireless connection to an eNode B, which is indicated with the antenna structure in the figure. Together, the LTE wireless and backhaul networks are known as the evolved packet system (EPS).

The primary nodes of the backhaul network are the SGW, the packet data network (PDN) gateway, and the mobility management entity (MME). The SGW serves as the local anchor in the backhaul network for Internet protocol traffic for individual UE. All Internet protocol traffic from external networks is first sent to the SGW. The SGW, in coordination with the MME, maintains awareness of exactly which eNode B the UE is connected to and then routes Internet protocol packets to that node. The

Figure 1.7
LTE/SAE Backhaul Network Design



SOURCE: wray castle Ltd., "LTE Voice Options and Operations," Bridge Mill, Stramongate, Kendal, UK, 2012.

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MME is the central control node for wireless UE in the LTE network and manages its connection status to individual eNode Bs. For example, when UE moves away from one eNode B and closer to another eNode B, the MME will reassign the UE to the second, now closer, eNode B. In other words, the MME manages the control plane of the wireless LTE network. The protocols running between the UE and the control network are known as the nonaccess stratum (NAS) protocols. The MME also manages specific Internet protocol connections to user equipment and can set up and establish individual Internet protocol connections as well as tear them down (these functions are known as EPS bearer control).

The PDN gateway is responsible for allocating Internet protocol addresses to UE, QoS enforcement, and flow-based charging. It is responsible for the filtering user downlink Internet protocol packets into the different QoS-based EPS bearers.

Two other important nodes in the LTE backhaul network are the policy control and charging rules function (PCRF) and the home subscriber server (HSS), which are also shown in Figure 1.7. The HSS contains user LTE network subscription data such as the user's EPS-subscribed QoS profile and roaming access restrictions. It also holds information about the PDNs to which the user can connect. In addition, the HSS holds dynamic information such as the identity of the MME to which the user is currently attached or registered. Finally, the HSS may also be integrated with the

LTE network authentication center (AUC), which performs user authentication and network access control functions.⁶

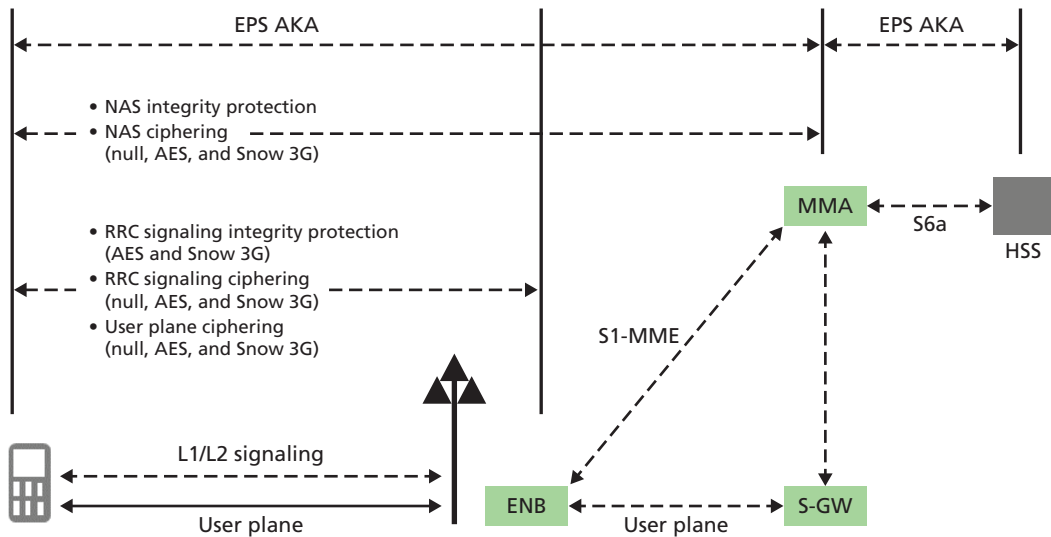
The PCRF is responsible for policy control decisionmaking. This server maintains subscriber account information also held by the HSS and ensures that individual subscribers gain access to network resources and are assigned the EPS barriers with QoS levels that are consistent with their subscriber account privileges.

LTE Security Architecture

The LTE security architecture is shown in Figure 1.8. The figure indicates the key nodes performing security functions as well as the links or interfaces between these nodes including links to the UE (indicated as a cell phone in the figure).

The MME and HSS provide the core security functions for the LTE network for both signaling and user data. When a UE attaches to the network, it is authenticated by the network by verifying the user’s subscriber data held at the HSS. Subscriber data are then forwarded to the MME that manages the initial UE network attachment. When the UE attaches to the network, the MME also provides security keys for protecting all EPS bearers established for UE communications. All data that go over the RAN are encrypted in the LTE network.

Figure 1.8
LTE/SAE Security Architecture



SOURCE: Alcatel Lucent, “LTE Evolved Packet System Architecture,” undated.
RAND MG1171/5-1.8

⁶ wray castle, 2012.

Figure 1.8 shows the encryption algorithms that can be used to protect the network control plane and user data. These encryption capabilities operate between the UE and the eNode B as well as between the other key LTE network nodes shown in the figure.

LTE Software Architecture

In contrast to the JTRS software architecture, there is no single LTE/SAE software architecture. Furthermore, LTE/SAE is not software-defined and competing vendors do not share software code. Instead, vendor products are built on competing chip sets. Equipment vendors develop products on specific chip sets using their own proprietary software code, which may, in some cases, use open source software at specific layers or in specific parts of their products (for example some vendor products may be based on the open source Linux operating system). Vendors can distinguish their products on the basis of user interface, look and feel, applications, etc. Because there is no single code base for LTE network equipment, LTE network interoperability is ensured by testing vendor products.

During the course of this study, RAND interviewed a number of industry participants from major cell phone network infrastructure providers. These interviews revealed that cell phone infrastructure providers perform a key function in the industry by testing user equipment handsets and other UE equipment for compatibility with their own network infrastructure products (such as eNode B terminals). In addition, they test their own network infrastructure products for interoperability and compatibility with the products developed by competing infrastructure providers. RAND found that industry participants conduct extensive testing to ensure that their equipment will be interoperable and conforms to 3GPP standards.

LTE Network and User Equipment Deployments

Commercial Network

The first commercial LTE networks were reportedly deployed in 2009.⁷ Since that time, a number of LTE network deployments occurred around the world. U.S. cellular telephone network service providers are in the forefront of the transition to LTE. Verizon wireless has deployed LTE in over 470 market areas throughout the United States as of the fourth quarter of 2012.⁸ AT&T wireless has deployed LTE in over 135 markets in the United States as of December 2012.⁹ Sprint had deployed LTE into 49 markets by the end of 2012 and promises additional deployments into 150 addi-

⁷ See “LTE (telecommunication),” Wikipedia, undated.

⁸ See Verizon, “LTE Information Center,” undated.

⁹ “AT&T Expands LTE Network to New Markets,” *LTE World*, December 21, 2012

tional markets soon.¹⁰ Many wireless carriers in Europe and Asia have also aggressively started to deploy LTE in their coverage areas.

DoD Deployments

The DoD is also exploring the use of LTE networks. Commercial off-the-shelf (COTS)–based communications technologies, including 4G/LTE broadband systems, may provide government users with high-capacity mobile communications that commercial users have come to expect from wireless broadband networks. In addition, commercial industry’s faster innovation time lines are often shorter than the longer acquisition schedules usually required to develop proprietary special-purpose government communications systems. Furthermore, if COTS systems and technologies can be leveraged by the DoD, they may provide government users with the latest advanced capabilities as they are introduced in the commercial markets.¹¹

The capability differences between tactical military communications and commercial COTS communications have appeared to diverge over the last two decades, leaving many in the military to wonder why they cannot achieve the same capabilities with the equipment they use on the battlefield as what they have become accustomed to in civilian life.

Figure 1.9 shows that developers of commercial waveforms have incrementally improved commercial mobile networks over time and that commercial firms have invested significant R&D resources into this progression. Below, we examine the resources that have gone into this development.

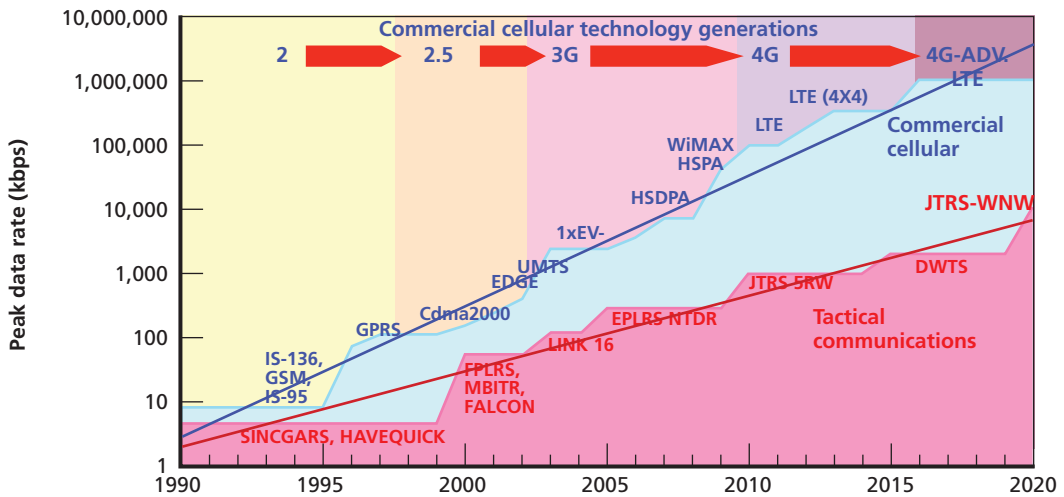
Figure 1.9 also shows how waveforms developed for the commercial mobile wireless cellular industry have evolved at least as “fast” as military waveforms (in terms of numbers of waveforms developed), and perhaps “faster” in terms of peak data rates. However, it is important to note that the difference in performance growth shown in the figure does not really compare equivalent capabilities. The commercial waveforms shown in the figure do not have the security features that military waveforms do. In addition, as we alluded to above, the JTRS GMR and WNW architecture is infrastructureless, which means that it is more survivable and adaptive than the LTE architecture that relies on fixed cell phone tower nodes. If a cell phone tower is destroyed, cell phone communications will not be available in the coverage area of that tower, unless overlapping coverage is available from another tower that is not damaged.

Nevertheless, it may be possible to adapt or modify the LTE architecture so that it can meet military requirements. Furthermore, using 4G/LTE in a military application would not be the first major use of COTS technology on the battlefield. The DoD

¹⁰ Michelle Maisto, “Sprint LTE Network Reaches 49 Markets, 150 More Coming Soon,” *eWeek*, December 20, 2012

¹¹ Douglas C. Smith, “Creating Opportunities through Improved Government Spectrum Efficiency,” Testimony before the House Energy and Commerce Committee, Subcommittee on Communications and Technology, Washington, D.C., September 13, 2012a.

Figure 1.9
The Data Capacity Gap: Tactical Versus Commercial Communications



SOURCE: A. R. Hartman et al., "4G LTE Wireless Solutions for DoD Systems," Military Communications Conference, 2011.

RAND MG1171/5-1.9

has transitioned to COTS technologies when government-funded proprietary systems failed to deliver capabilities similar to their civilian counterparts. Commercial laptop computers and tablet devices such as Apple's iPad are commonly used throughout the U.S. military. "In years past, the Pentagon probably would have spent billions of dollars creating its own custom devices, but modern technology offers a much cheaper alternative."¹²

Using this 4G technology has many potential advantages. First, the technology development life cycles of commercial cellular systems are much faster than those of current military systems. By leveraging the continual and extensive R&D investment from the commercial sector, the military can remain on the leading edge of advances in waveform standards, network equipment, and handset equipment. For no extra cost, the military gains the benefit of the commercial rapid technology life cycles and low cost factors. Second, "use of commercial wireless broadband technologies, when appropriate to meet mission needs, can allow military and other Federal government operations to use spectrum even more efficiently and cost-effectively."¹³ Finally, by using the same waveform, standards, and similar equipment, military forces can ensure interoperability with civilian forces that they may work alongside during homeland defense and natural disaster situations.

¹² W. J. Hennigan, "Taking iPads into Battle," *Los Angeles Times*, September 25, 2011.

¹³ Smith, 2012a.

Although all services are currently testing potential 4G/LTE applications, the U.S. Navy was deploying a test system in early 2013. A 4G LTE network was to be operationally tested on the USS *Kearsarge*, the USS *San Antonio*, and the USS *Whidbey Island* beginning in 2013. A team led by Oceus Networks, an offshoot of Ericsson, developed this system, also known as the NAVY 4G /LTE afloat. The baseline capabilities of this network will provide high-speed Internet at 8–15 Mbps. “The 4G systems on all three ships will have a line-of-sight range of 15-20 miles, which can be extended to 30 miles with the use of a base station on a Marine H-1 helicopter.”¹⁴

For the first deployment with the USS *Kearsarge*, 200 Marines will be outfitted with Android handsets with standard smart phone capabilities such as voice, text, data, full motion video (FMV), navigation, blue-force tracking, biometrics, and a high-resolution camera. The built-in Global Positioning System (GPS) capabilities paired with the blue-force tracking application within the phones will allow the deployed Marines and their commanders to track each other’s positions in real time. The first versions will be authorized to transmit only unclassified information, but Naval Air Systems Command is “working with the NSA to create a solution that will allow the phones to transmit classified data.”¹⁵ The system will interface directly with ships’ existing Automated Digital Network System (ADNS) and Distributed Common Ground Station–Intelligence Community (DCGS-IC) enterprise services.

The deployed test equipment has the capacity to support up to 3,500 Marines and sailors deployed with an Amphibious Ready Group (ARG). Using the 4G/LTE waveform, similar interoperable baseline systems in an airborne configuration can support communications up to 60+ miles. This capability, combined with session handover and scalable capabilities, could aggregate into a virtually unlimited coverage area. Such a network would allow a military unit conducting combat operations in an austere environment to have connectivity to each other similar to what they experience with their personal smartphones in civilian life. Multiple base stations on airborne platforms could theoretically provide countrywide communications. The ability to create the functionality of a full cellular network in a single unit on a mobile platform overcomes limitations of applications with fixed switching equipment. The mobile network equipment application “can be placed aboard ships, installed in tactical warfighter vehicles, mounted on UASs [unmanned aircraft systems] and other aerial vehicles, and/or be soldier back-packed.”¹⁶

The Navy’s 4G/LTE Afloat project designates 4G as a “mission critical requirement” for the Counter-Piracy Task Force, which mostly operates off the Horn of Afri-

¹⁴ Bob Brewin, “Naval Air Systems Command Plans 4G Cell Service aboard Ships,” *Nextgov.com*, April 12, 2012a.

¹⁵ Brewin, 2012a.

¹⁶ Smith, 2012a.

ca.¹⁷ This network could be used to send critical intelligence including airborne FMV to Marines before they boarded vessels captured by pirates or terrorists. It could also be used to relay critical real-time intelligence back to the ARG command element on the USS *Kearsarge*.

Although the Navy's 4G/LTE Afloat project is the first to be tested operationally, many other similar efforts are currently ongoing. Other test applications of 4G LTE within the DoD include the following:

- A Navy pilot program was scheduled to go on a UH-1 in November 2012. In this application, a base station, eNodeB, and an EPC was to be carried on a UH-1. The intent of this demonstration was to create a full-blown 4G/LTE airborne network for anyone on land or sea with line of sight to connect.
- Oceus Networks is working with the Gorgon Stare program to fly on that platform. This test will investigate the possibility of replacing or supplementing elements of the current tactical datalink.
- Teams are working with the Joint Special Operations Command (JSOC), testing on a Pilatus PC-12 and a C-130 wing pod to provide LTE coverage from the air. If the initial test is successful, it may become a Joint Capability Technology Demonstration (JCTD) initiative.
- Teams are working with elements of the U.S. Air Force to determine whether multiple MQ-9 Reaper UAS systems can be flown around a large geographic area to provide countrywide coverage.
- Teams are working with the Air Force BIG SAFARI to test the LTE application on smaller air platforms, with receivers on UASs. "BIG SAFARI is the USAF's program office responsible for sustainment and modification of specialized special mission aircraft."¹⁸
- Research is also being conducted, especially in air applications, to model and study performance, fading effects, and Doppler effects for airborne applications.

The DoD is not the only government agency looking at potential uses for this type of mobile network. The FCC is investigating the possibilities of putting a base station and core network on a weather balloon at 100,000 feet to provide first-responder state-wide coverage for civilian and military applications. The FCC has begun a major effort to study how deployable aerial communications architecture (DACA) "can restore the communications capabilities of first responders shortly after the occurrence of a major natural disaster or terrorist attack."¹⁹ Equipment similar to that currently being tested under the Navy program on the UH-1 could fly on weather balloons or high-altitude/

¹⁷ Neal Ungerleider, "The 4G System That Powers The Navy's Pirate Fights," *Fast Company*, April 19, 2012.

¹⁸ Federation of American Scientists, "Big Safari," FAS Intelligence Research Program, July 30, 1997.

¹⁹ Smith, 2012a.

long-endurance UASs. This airborne network could provide emergency communications to local, state, and federal government agencies and personnel after a major disaster or terrorist attack if the terrestrial communications infrastructures were disrupted, damaged, or destroyed. 4G LTE equipment vendors are developing rapidly deployable aerial communications systems that can provide immediate broadband communications to disaster areas.²⁰

4G/LTE has the potential to provide solutions to many gaps in tactical communication architectures, but there are limitations. Many fielded tactical networks in the military differ from their civilian counterparts in that they provide secure communications and in some cases antijam capabilities. Efforts are currently ongoing with 4G/LTE equipment and standards to meet secure communications requirements. Creating an antijam capability outright through techniques such as frequency hopping may prove challenging—without losing commonality and interoperability with civilian 4G/LTE waveforms and equipment.

Although commercial 4G/LTE systems have many builtin security features, the Defense Information Systems Agency (DISA) and NSA have determined that more work is required to meet military security requirements. The Naval Air Systems Command is working on standards to scramble or encrypt any storage that exists on the phone to facilitate NSA requirements. DISA and NSA understand that it is too difficult to keep up with all the commercial LTE software and hardware releases. NSA is in the process of giving direction on what it would like to see as far as password aging and password complexity, resulting in standards on encryption of data in storage on LTE devices. The Navy pilot program has been through Joint Interoperability Test Command (JITC) certification. The current 4G/LTE solution has completed IA certification on land and mobile devices and is now progressing toward maritime and air certification.

4G/LTE is a commercial waveform and has limited frequency-hopping capabilities. The Defense Advanced Research Projects Agency (DARPA) has investigated similar antijam waveforms, but the derivative product is a highly proprietary waveform that requires proprietary handsets and base stations. Although this approach has unique applications, it is a separate effort and would not benefit from the massive amounts of civilian research and development spent on 4G LTE. There are efforts to apply techniques previously developed through years of testing to counter GPS jammers. These techniques have proven successful in allowing the military unfettered use of GPS in jamming environments. Although there are some very basic differences between GPS and 4G/LTE frequencies and waveforms, the techniques and procedures developed to counter GPS jamming show promise for the use of 4G/LTE waveforms and equipment in jamming environments. These techniques are planned for future integration into this test application.

²⁰ Smith, 2012a.

Comparison of Development Approaches and Organizational Structures

In this section, we compare the development approaches and organizational structures responsible for the development of the JTRS family of programs and for LTE.

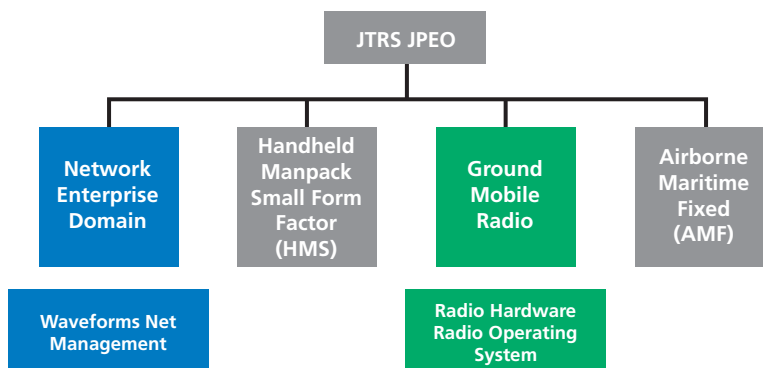
JTRS Development Organizations

The JTRS program consists of a family of software-defined radios and waveforms designed to be easily interoperable. All JTRS radio hardware is SCA-compatible, meaning that all hardware shares a common software framework for waveform development and integration. The use of SCA on base radio hardware will enable a common set of waveforms to be ported to different radio hardware.

Here, we describe the organizational structure for the family of JTRS programs that was responsible for the development of all JTRS SDRs from 2005 to 2012. The JTRS organizational structure is shown in Figure 1.10. All JTRS programs of record were placed under the oversight of a JTRS Joint Program Executive Office (JPEO). JTRS radio hardware and waveform software are developed independently under the oversight of different program offices and, in some cases, different contractor teams (for example, GMR and WNW are under the same prime contractor but different sub-contractors). WNW was developed by the JTRS NED program office, and, as noted above, WNW is based on the JTRS SCA. The development of other JTRS networking waveforms was also the responsibility of the JTRS NED program. The SCA was developed by an industry consortium with strong leadership from the JTRS JPEO. The JTRS GMR program office was responsible for developing radio hardware designed to run WNW and was also responsible for GMR field testing.

The JTRS JPEO was responsible for ensuring coordination between JTRS programs. Although WNW was developed by NED, and GMR was developed by the

Figure 1.10
JTRS Organizational Structure



GMR program, the JPEO ensured that the products developed within the individual programs were interoperable and compatible with each other.

A key architectural construct that the JPEO itself was responsible for was the SCA that was to be used by all JTRS programs. The SCA provided a framework for software development that was used by both the hardware and software programs. In this regard, it is important to note that JTRS hardware programs (i.e., the programs that actually built the radios) also were responsible for developing the operating systems for these radios. JTRS radios are software-defined, which means that they resemble personal computers (PCs) in many respects. Like a PC, a JTRS radio would have an operating system on which waveforms could be loaded. The user can load applications on to the PC, just as would be done with a Windows PC using Windows OS. The SCA is the framework the radio OSs had to conform to as well as the waveforms. It helped to ensure that waveforms would be portable across hardware platforms (could be designed and developed on one hardware platform of the JTRS family of radios and ported to other platforms in the family).

The development of JTRS waveforms was the responsibility of the JTRS NED program, and the development of JTRS radios was the responsibility of a number of programs as indicated in the figure. The particular waveform we focus on in this analysis is WNW, which is the most complex waveform developed by any of the JTRS programs. Originally, WNW was developed to run on only a single JTRS radio (GMR), which was the most complex and costly hardware platform developed in the JTRS family of radios.

One potential challenge associated with the JTRS organizational structure is ensuring that products developed by different programs are compatible and work together as originally envisioned. At the time the JTRS program was created, the PC was the dominant consumer computing platform in which hardware and software development was separated in commercial industry. (Microsoft made the software, and Intel and other original equipment manufacturers [OEMs] made the hardware.) The advantage of this approach was that competition among hardware OEMs reduced the price of PCs and enabled them to dominate the market for low-cost computers. However, as the Windows architecture aged, and as other companies introduced smaller, more mobile computing platforms that were more power efficient than PCs, they began to be preferred by consumers. These new mobile computing devices also turned out to have radio capabilities and have become increasingly important parts of the consumer electronics market. These include the Apple iPhone, mobile devices operating the Android OS, as well as BlackBerrys. Therefore, for commercial wireless and mobile devices, it appears that much tighter integration is required for hardware and software, which is in contrast to the JTRS organizational structure.

The JTRS organizational structure could work if hardware and software development could be easily separated and if it could be developed effectively in separate organizations. However, it should also be pointed out here that the JTRS SDR architecture,

which is based on the SCA, is in some important ways different from the PC hardware and software architecture. Most PCs do not provide wireless communications capabilities and do not require specialized antennas, power amplifiers, and A/D converters, as SDRs do. These components, which are unique to digital radios, make it more difficult to separate the “software stack” and OS functions from hardware. Indeed, this is perhaps one reason why commercial industry has chosen not to adopt an SDR approach for the LTE architecture.

The JTRS program has encountered significant instability and several program restructurings as a result of cost growth, requirements changes, schedule slips, and difficulties in meeting stated or implied requirements. These have led to a subsequent Nunn-McCurdy breach for the JTRS GMR program.²¹ In fact, the JTRS program has undergone a number of reorganizations within the past several years that have resulted in the following:

- cancellation of JTRS GMR program²²
- cancellation of the JTRS AMF program²³
- phase-out of the JTRS JPEO and transition to the Joint Tactical Networking Center (JTNC)²⁴
- phase-out of the JTRS NED program and transition to the Joint Tactical Network (JTN) program.²⁵

In addition to the cancellations and phaseouts mentioned above, restructuring efforts also resulted in the

- continuation of the JTRS HMS program²⁶
- continuation of the JTRS Multifunctional Information Distribution System program.²⁷

²¹ J. Michael Gilmore, *DoD Operational Test and Evaluation FY 2011 Annual Report*, Washington, D.C.: Department of Defense, 2011.

²² JTRS GMR–SAR, “Selected Acquisition Report,” Department of Defense, December 31, 2011.

²³ *Airborne & Maritime/Fixed Station Joint Tactical Radio System (AMF JTRS)*, “Selected Acquisition Report,” Department of Defense, December 2012.

²⁴ Bob Brewin, “Pentagon Shuttters Joint Tactical Radio System Program Office,” *Nextgov.com*, August 1, 2012b.

²⁵ Barry Rosenberg, “From Radios to Waveforms: How JTRS Is Remaking Itself as JTNC,” *Defense Systems*, September 6, 2012.

²⁶ Rosenberg, 2012.

²⁷ Rosenberg, 2012.

As noted in the list above, the JTRS JPEO was formally disestablished in July 2012.²⁸ Before this decision, the JTRS GMR and AMF programs were canceled in 2011. However, it appears that the JTRS networking waveforms developed by NED and tested on several prototype JTRS hardware platforms such as GMR will still be fielded and used on other SDRs developed by other vendors. For example, the SRW waveform has been ported to the Harris PRC-117G, and WNW may be ported to several other industry-developed SDR platforms. In the same memorandum that disestablished the JTRS JPEO, the JTRS NED program was renamed the JTN program. Responsibility for the development and maintenance of the SCA was assigned to the JTN program.

All of these organizational changes suggest that the JTRS program was troubled and that the attempted solutions included, in part, changes to the program structure. We explore this question in more detail below.

LTE Development Organizations

LTE is a family of systems that forms an integrated cellular communications architecture. This architecture is designed so that system products from different vendors can be integrated into the same network (i.e., they are interoperable). LTE is a family of waveforms and architecture for next-generation cellular telephone networks that will eventually unify data and voice communications networks into a single Internet protocol network. To date, it is the most advanced and complex terrestrial waveform development in the commercial world.

LTE includes a set of standards developed by 3GPP for mobile 3G and 4G mobile communications. The currently fielded standard is LTE Release 8 (December 2008). The mobile standard is Evolved UMTS [Universal Mobile Telecommunications Standard] Terrestrial Radio Access (E-UTRA) and the base station standard is Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). Given that LTE is not software-defined, standards apply to both LTE software and hardware.

LTE development is based on a much different organizational model than the one for the JTRS family of programs discussed in the preceding section. LTE is being developed by a large and complex international organization-of-organizations known as 3GPP.²⁹ 3GPP “unites six telecommunications standard development organizations . . . known as ‘Organizational Partners’ and provides their members with a stable environment to produce . . . reports and specifications that define 3GPP technologies.”³⁰

The telecommunications standard development organizations involved in 3GPP are:

²⁸ JTRS GMR-SAR, 2011.

²⁹ 3GPP, “The Mobile Broadband Standard,” website, undated-b.

³⁰ 3GPP “About 3GPP,” website, undated-a.

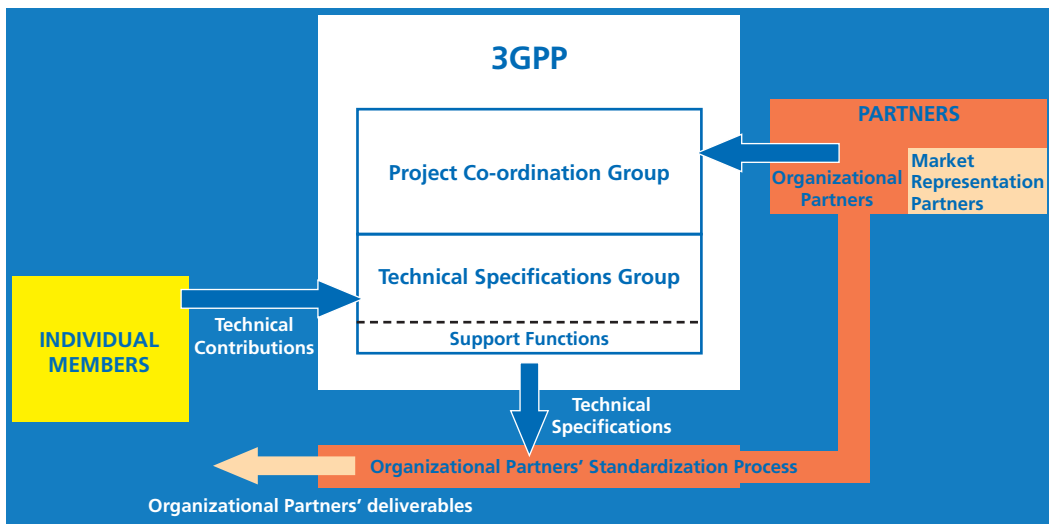
- the Association of Radio Industries and Businesses, Japan
- the Alliance for Telecommunications Industry Solutions, USA
- China Communications Standards Association
- the European Telecommunications Standards Institute
- Telecommunications Technology Association, Korea
- Telecommunication Technology Committee, Japan.

In addition, there are 13 market representation partners and 378 individual members.

The organizational structure of 3GPP is not focused on developing hardware and software products but rather on developing technical standards that can then be used by competing firms to develop hardware and software products.

The 3GPP organizational structure is shown in Figure 1.11. Industry and technology experts from individual member firms form technical specification groups that develop technical specifications for new systems as indicated in the figure. For a large, complex system such as LTE, the technical specification group may establish sub-working groups that develop technical standards for specific parts of the architecture design. These technical specifications are reviewed by the 3GPP organizational partners and may be revised accordingly. Once such technical specifications are approved

Figure 1.11
LTE Organizational Structure



SOURCE: 3GPP, "Third Generation Partnership Project (3GPP) Partnership Project Description," April 12, 1998.

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they can be used in the design of new telecommunications systems. Technical experts who are not employed by individual 3GPP member companies or who are not members of 3GPP organizational partner committees may not participate in 3GPP technical specification working groups. One key value in being a member firm is having the ability to influence the technical design and specification of next-generation telecommunications systems.

One challenges with developing a set of standards for 4G cellular networks is achieving cooperation among a very diverse set of industry firms that sometimes operate and compete in the same markets and sometimes in different markets around the world. Another challenge is ensuring that the standards developed by the organization lead to interoperable products because a common software platform is not assumed or used. The consensus-oriented process used by 3GPP helped maintain the interoperability of a system based on components from multiple competing developers.

The 3GPP organization grew out of the European standards development process that was used to develop technical standards for the second-generation (2G) digital mobile phone system, Global System for Mobile Communications (GSM). The GSM standard was developed by the European Telecommunications Standards Institute (ETSI), which is an independent, nonprofit, standardization organization composed of equipment-makers and network operators in Europe. The GSM standard was widely adopted in Europe, but other competing 2G mobile phone standards and systems were developed and deployed in Asia and the United States.

At the conclusion of the GSM development, ETSI members turned their attention to the development of technical standards for a new 3G mobile phone system standard. ETSI and other Standards Development Organizations (SDOs) initiated discussions on development of a UMTS for 3G mobile phone systems that could be used in all regions of the world. Such a standard would enhance mobile phone interoperability and make it easier for users to roam on other mobile phone networks outside their home countries.

In 1998, a group of SDOs interested in UMTS formed 3GPP by signing the 3rd Generation Partnership Project Agreement. The original task of 3GPP was to produce technical specifications and reports for UMTS.³¹ The UMTS was developed rapidly and was released in 1999. Later, 3GPP was given the task of maintaining the GSM standard and, later, of developing LTE technical specifications.

Summary

The organizational structure of the JTRS family of programs has changed at least three times during its lifetime. The number of perturbations in the organizational structure because of program instability, uncontrolled cost growth, and schedule delays has contributed to subsequent program cancellations and restructuring. Whether these

³¹ "UMTS 3G History," *Radio-Electronics.com*, January 2, 2013.

restructuring efforts have effectively curtailed cost growth and program instability remains to be seen. In contrast, the LTE development has proceeded under the same 3GPP organizational structure for the entire development. Furthermore, 3GPP has added new working subgroups as required that focus on defining standards for specific components of the larger architecture.

It should also be noted that LTE designers changed LTE system requirements for the initial releases (Release 8 and 9) when it was determined that some requirements would be difficult to meet (e.g., integrated voice and data on the same backhaul network).³² These changes will be reflected in Release 10. 3GPP may also be establishing a related working subgroup to address these technical challenges.

In summary, LTE's organizational structure is intentionally designed to be flexible to enable the organization to address technical challenges as they arise. In contrast, it is not clear that the program reorganizations that the JTRS program has gone through have resulted in an organizational structure with the same ability to deal with unforeseen technical hurdles.

A Comparison of Technical Performance and Development Time Lines

In this section, we compare the technical performance characteristics and the development schedules for the LTE and JTRS GMR and WNW communications systems. In particular, we investigate the questions of how similar or different these systems and waveforms are, and whether one or the other system required more time to develop.

Technical Performance Comparison

Some characteristics of the two systems are quite different, but other aspects are quite similar. We review the major characteristics of each system below. First, we note that the security architectures of the two systems are quite different, as is the protocol by which users are authenticated in the two networks. Furthermore, user message traffic is prioritized and controlled in a different way in each network. The LTE architecture includes subscriber account–based QoS channel (or EPS bearer) network resource access controls, whereas WNW instead employs a message-based QoS scheme, where individual users can independently choose the priority of the messages they send (five priorities are available to select from). The presence of the latter type of QoS scheme is not surprising in a peer-to-peer network that has no centralized control authority. In contrast, in the LTE architecture, the network service provider can deny network resources to subscribers according to its own policies and the account status of the subscriber. As indicated in the section comparing development approaches and struc-

³² The “cell towers” of wireless mobile communications networks are connected to other the cell towers and the core network of the mobile communications provider by means of a backhaul network. The backhaul network may refer to a wire line or fiber optic network, or high-capacity wireless links.

tures, the LTE network has a hierarchical structure where network resource access control decisions are centrally managed by the HSS and PCRF nodes. And, finally, it is important to note that user bandwidth usage is monitored in the LTE network, so that the network service provider can bill users according to their network usage (e.g., the number of voice minutes or data packets consumed per month). In contrast, such user monitoring and billing functions are absent from the JTRS WNW network.

Despite these differences, some portions of the wireless communications waveforms used in both systems are quite similar. The wireless radio frequency interface of WNW and LTE uses similar radio signal modulation schemes, but there are important differences as explained below. Further, in some respects the LTE waveform is more advanced than that used by WNW. The WNW wireless communications waveform uses symmetric links; that is, the radio frequency characteristics of the uplink and downlink from a particular GMR terminal are the same. The LTE wireless channel is asymmetric. Each LTE wireless channel is defined as a link between the eNode B and the UE. The LTE downlink is defined as the wireless signal that is transmitted from the eNode B to the UE, whereas the LTE uplink is defined as the wireless signal from the UE to the eNode B.

Both LTE and WNW use similar orthogonal frequency-division multiplexing (OFDM) or orthogonal frequency-division multiple access (OFDMA) waveforms for the downlink.³³ OFDMA is spectrally efficient and enables multiple carriers to be closely spaced. However, LTE uses a different waveform on the uplink, single-carrier frequency division multiple access (SC-FDMA). As the name implies, SC-FDMA is a channel allocation managing communications from multiple users that share the same frequency band. In that sense, it shares many characteristics with OFDMA. However, SC-FDMA is more power-efficient than OFDMA, making it better suited for smaller, power-limited UE devices (such as mobile phone handsets).

WNW and LTE have different downlink and antenna capabilities. WNW assumes the use of a single L-band antenna. LTE can use multiple antennas on both the downlink and uplink. The minimal implementation of the LTE standard assumes that (1) the eNode B transmits the downlink on two antennas and receives the uplink on a single antenna and (2), the UE receives on two antennas and transmits the uplink on a single antenna. In addition, the LTE standard allows for additional, more powerful multiple-input and multiple-output (MIMO) capabilities for both the eNode B and UE, as indicated in Table 1.1. Eventually, both 2-by-2 and 4-by-4 MIMO LTE terminals will be possible where both the terminal transmitter and receiver can use two or four antennas. MIMO provides several advantages for wireless communications. It can reduce sensitivity to channel noise and multipath and provides increased processing gain for weak signals (although it requires increased computational power to pro-

³³ L3 Communications, *Wideband Networking Waveform OFDM PHY*, undated.

Table 1.1
Technical Performance Metrics

	LTE/SAE				WNW
LTE Rel 8 User Equipment Cat.	1	2	3	Max.	
Channel bandwidth(s) (MHz)	1.4, 3.0, 5.0, 10.0, 15.0, 20.0				1.2, 3.0, 5.0
Peak rate: uplink (Mbps)	5	25	50	75	5
Peak rate: downlink (Mbps)	10	50	100	300	5
Node join (sec)	100 ms				< 60 sec to add 1 node to network < 120 sec to add 8 nodes to network
Data message latency (ms)	100 ms data LTE standard for voice is to be determined				100 ms 75 ms for tactical voice—later dropped
Network formation (sec) ^a	n/a				< 15 min in 150 node network
Network node scalability	1,000s—at wireless tier 10,000s				No formal requirement, but implied need to support ~1,500 nodes (FCS-GAO) 30 nodes (achieved as of 2012)
Security	AES 256 for user and control plane traffic				At multiple levels, Type 1, MIILS
Modulation (downlink)	OFDM (QPSK, 16QAM, 64QAM...)				OFDM (similar)
Modulation (uplink)	SC-FDMA				OFDM
2x1 MIMO	Mandatory				Not supported
2x2 MIMO	Not supported	Mandatory			Not supported
4x4 MIMO	Not supported	Mandatory			Not supported

SOURCES: Andrei Traian, "An Overview of Long Term Evolution Advanced," Saint Louis, Mo., undated, Motorola, "Long Term Evolution (LTE): A Technical Overview," Technical White Paper, 2007; Alcatel Lucent, "The LTE Network Architecture: A Comprehensive Tutorial," Strategic White Paper, 2009. Joint Tactical Radio System Operational Requirements Document, revision 2.3, 2002; JTRS NED SAR, "Selected Acquisition Report," Department of Defense, December 31, 2011; Government Accountability Office, 2008.

^a Applicable to WNW and MANETs only.

cess multiple input and output signals). JTRS GMR and WNW do not have MIMO capability.

Table 1.1 indicates that LTE performance is superior to that of WNW in several important areas. First, LTE channel bandwidths are up to four times larger than those available for WNW. This means that LTE can use more spectrum (if it is avail-

able) than WNW. Also, LTE peak user data rates are higher than those available with WNW, especially in the downlink. This is not surprising because LTE eNode B antennas are fixed and can provide more gain and power than a GMR vehicle-mounted radio. More important, the performance difference between LTE and WNW is much larger for large networks. The peak data rates shown are characteristic of a two-node network. For networks of larger sizes, the average data rate to a single node will be smaller than the peak data rate. The average data rates provided in these networks is a function of their spectral efficiency. The peak data rates shown in Table 1.1 require some explanation. The WNW peak data rate shown is for the entire WNW wireless channel, which includes the channel bandwidth needed for the control plane (which allocates modulation, power, and bandwidth settings that each node should use in the shared channel). Field tests of GMR and WNW reveal that the control plane takes up progressively more bandwidth as the number of nodes in the WNW network is increased and even more when a significant fraction of the WNW nodes are mobile. This is because WNW, in contrast to LTE, is an infrastructureless network design, so when network resources have to be changed because of network topology changes, WNW nodes have to negotiate and reallocate network resources (e.g., time slots) to try and optimize network performance. On the other hand, the LTE RAN is centrally controlled by the eNode B. In the LTE RAN, much less negotiation is required, which limits LTE control plane traffic. With a channel bandwidth of 20 MHz, LTE can achieve a spectral efficiency of over 6 bits per Hertz, which is much higher than the spectral efficiency of WNW observed in field tests.³⁴

It is unlikely that the greater security capabilities of WNW cannot explain all the differences in performance highlighted in Table 1.1, especially for user data rates and network sizes. The latter is especially important, as LTE wireless networks can scale up in size to support over 1,000 nodes (UEs) from a single eNode B. Some of these differences are probably due to the more advanced technologies used in LTE that are not available in WNW (e.g., MIMO antenna processing), in addition to the performance penalties incurred by WNW as a result of its substantial security requirements. However, another important difference—maximum supported network size—is due to the more demanding operational environment that WNW nodes are designed to operate in. WNW supports full MANET operation, where all nodes in the network can be mobile. In contrast, in an LTE network, only UE nodes are designed to be mobile. The eNode B nodes are designed to remain stationary, which greatly simplifies aspects of the network design and network management.

Another aspect of the two network designs that is also substantially different (and not alluded to in Table 1.1) is network control functions. In the LTE network architecture, network control functions are built into specific nodes, described in the section above, that reside in the backhaul network and in the eNode B. UE mobile

³⁴ In this unclassified publication, we cannot provide an estimate of WNW spectral efficiency.

handsets have minimal network intelligence and control capabilities built into them. This enables mobile handsets to be smaller, to consume less power, and to be less costly.

In contrast, the WNW network design is entirely different. WNW network and control capabilities are built into each node. This eliminates the need for one or more control nodes in a WNW network but significantly increases the intelligence and processing power requirements for GMR WNW terminals. This in turn resulted in the larger size, processing power, and prime electric power requirements for the GMR. Although the WNW network design enables peer-to-peer networking and robust and survivable network design, it raises the cost of each network node considerably.

Comparison of Development Time Lines

Both LTE and JTRS WNW are the products of extensive requirements processes that incorporate high-level guidance and priorities from key stakeholders. First, we review the development time line for JTRS and WNW.

JTRS and WNW

The JTRS program was originally started in response to high-level strategy. In August 1997, the Joint Requirements Oversight Council (JROC) approved a mission needs statement for a JTRS. Six months later, in March 1998, it approved the operational requirements document for a joint tactical radio program. The DoD structured this acquisition program to fulfill goals established by Joint Vision 2010.³⁵ Joint Vision 2010 posited that, because of an increasingly lethal battlespace caused by technology advances, a prudent posturing strategy should include the ability for “greater mobility and increased dispersion” of military personnel; this tactical structure requires “additional communications and coordination capabilities” to synchronize these dispersed elements.³⁶ At the time, no proven technical solution existed. Acquisition officials determined that a new JTRS program would serve as the technical solution to these broad military goals.

The JTRS program suffered requirements perturbations early in its development. Some requirements changes likely resulted from interactions between industry and program officials, as program officials sought to determine technology limits. The Army held an Industry Day on June 27, 2000, with the stated purpose “to discuss the overall strategy for and structure of the Army’s program from the present development phase to the production phase of the JTRS.”

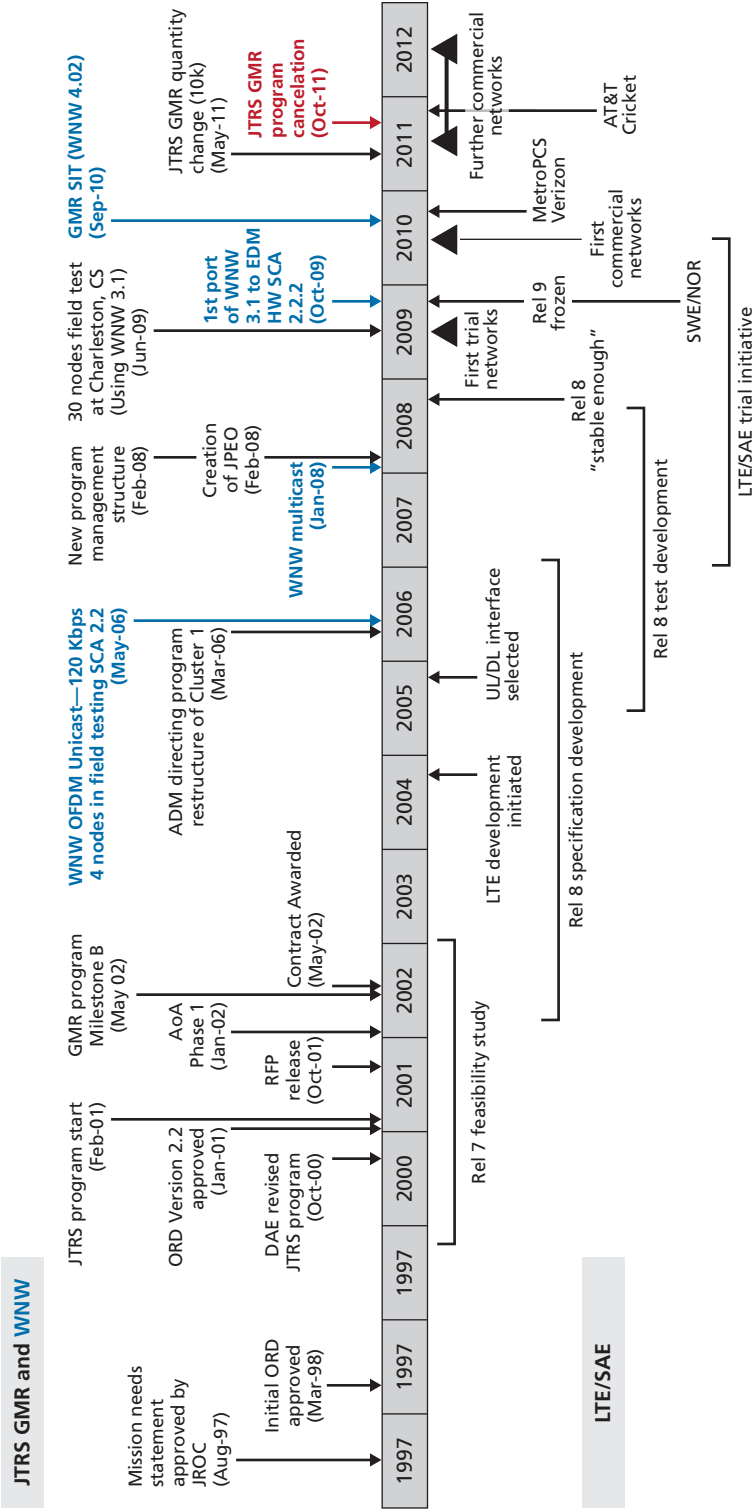
Figure 1.12 shows that the JTRS requirements development process spanned about six years. The ORD for the JTRS program went through several iterations from March 1998 to April 2003, when Version 3.2 was published.³⁷ In the interim, the

³⁵ Chairman, Joint Chiefs of Staff, *Joint Vision 2010*, Department of Defense, undated.

³⁶ Chairman, Joint Chiefs of Staff, undated.

³⁷ See Bob Arguero, “Army to Hold Joint Tactical Radio System Industry Day,” *GovCon*, June 20, 2000.

Figure 1.12
Development Time Line



program office released a request for proposal (RFP) in October 2001, four years after the release of a related mission needs statement and a year and a half before the final ORD. In January 2002, the DoD completed the JTRS Analysis of Alternatives (AoA). In May 2002, the DoD awarded a contract to Boeing for delivery of JTRS Cluster 1 (which would later be called JTRS GMR). JTRS Cluster 1 included both the hardware and software for the radio under a single contract. The Army served as program manager for this contract.

In 2005 the Cluster 1 program encountered a number problems. These problems included size and weight issues (the radio was too big), interoperability concerns, as well as issues associated with its security architecture (it used software-based encryption).³⁸ These issues prompted a major restructuring of the program in March 2006, splitting the hardware (now called GMR) and software (SRW/WNW waveforms) into two distinct programs: JTRS GMR and JTRS NED, each subject to its own testing and schedules.

Also shown in Figure 1.12 are key milestones in the development of WNW. The first WNW field demonstration took place in May 2006 when four GMRs formed a network and collectively transmitted data at a rate of 120 kbps. Waveform development proceeded over the next five years or so until WNW was tested in a network of 30 nodes in 2009. In late 2009, WNW was ported to the final version of GMR hardware, the so-called engineering development model (EDM) version of GMR. The EDM GMR was tested in networks of up to 30 nodes in 2009 and later at the GMR system integration test (SIT) in September 2010. The program was never able to demonstrate a working network of 70 to 120 nodes, which was the preferred range of network sizes needed to network all senior leaders of an Army BCT.

The JTRS GMR suffered cost growth in 2008 and again in 2011, ostensibly because of a reduction in the total number of radio units needed for the entire Army force after the cancelation of the FCS program. Previous RAND research on the root cause of JTRS GMR program cost growth, indicates that the reduction in units likely occurred because of system capability issues and not because of exogenous factors.³⁹ It is important to note that the cost growth seen in the GMR program was not mirrored in the NED waveform program. Nevertheless, WNW scalability limits as well as GMR size, weight, and power issues prompted the reductions in the quantity of radios purchased and subsequent unit cost growth. In October 2011, DoD cancelled the JTRS GMR program.

In summary, the JTRS requirement development process took approximately six years. The actual development of the JTRS GMR and WNW took approximately nine

³⁸ Andrew Feickert, "The Joint Tactical Radio System (JTRS) and the Army's Future Combat System (FCS): Issues for Congress," DTIC Document, November 17, 2005.

³⁹ The RAND report is not available to the general public.

years, from 2002 to 2011. The development of GMR and perhaps WNW were stopped before it was shown they could meet their program requirements.

LTE and SAE

The bottom of Figure 1.12 provides a time line for the LTE development process that began in 1999. The reader will recall that 3GPP was formed in 1998 and initially was given the task of creating the UMTS standard for 3G cellular networks. Shortly after that standard was released in 1999, 3GPP was given the new task by its leaders to develop a new standard for 4G wireless cellular networks that improved on the 3G standard and that could provide greater data communications capacity for network users.

LTE also required a significant amount of time for requirements development. This took about five years starting in 1999 and concluded in 2004. But in reality, some requirements have continued to change for the LTE system as system development proceeded and as test data became available. Early LTE test results influenced system design and improvements and have resulted in the evolution of LTE requirements over time. This was especially true in the development of the planned Internet protocol-based voice capability for LTE.

LTE development was initiated formally in 2004. The LTE wireless user uplink and downlink waveforms were selected in 2005. The first version of LTE was labeled Release 8 and was completed by the end of 2006. However, one can see from the figure that a considerable amount of time was devoted for testing of Release 8—from mid-2005 to late 2008. It was not until late 2008 that Release 8 was stable enough to be used in the first trial networks.

The first field tests of LTE Release 8 took place in 2009. At about the same time Release 9 was frozen, which was the first version of LTE that has been deployed on a widespread basis in commercial networks. The first commercial deployments took place in mid-2010. By 2011, LTE Release 9 was deployed on a large scale in all major regions of the world.

One can see from the time line in Figure 1.1 that initial LTE requirements development took about six years to complete, from 1999 to 2004. But one should be aware that LTE requirements development was not fully completed then and future versions or releases of the LTE standard are planned. It is important to note that it will not be until Release 10 that a fully integrated LTE network solution will be provided. Release 10 will provide both integrated voice and data communications capabilities in the same IP-based backhaul network. LTE Release 8 and 9 do not provide such a capability. In current LTE networks, voice communications are provided by the 3G network.

Cost Comparison

JTRS Development Costs

In attempting to compare the development strategies of LTE and WNW, a necessary task is comparing total costs. Although ideal cost comparisons would isolate hardware and software development, as well as program management costs, as illustrated above, the original iteration of the JTRS program integrated both the hardware and waveforms into one program, to facilitate management of program interdependencies. Available data provide only a rough cost division of both efforts. Further, the restructure in 2006 that separated both programs possibly shifted faults of WNW development into GMR costs through unit reductions. Thus, the most accurate cost for the development of the JTRS WNW capability is combined software (WNW/SRW) and hardware (GMR) RDT&E costs as reported by the DoD.

Over the course of the program, DoD invested \$3.2 billion in the development of JTRS GMR and NED, resulting in a canceled GMR and a functioning WNW waveform. As discussed elsewhere in this chapter, the dollar value invested in JTRS RDT&E is much smaller than the amount invested in the creation of the fully functioning LTE waveform. However, the obvious question is whether the dollar value invested is the driving factor for the JTRS failure or whether other consequential differences resulted from the government/industry partnership nonexistent in self-interested, private-market collaboration. A fundamental question arises about the ability of a government acquisition program to fund and adequately incentivize single contractor development of unproven technology, regardless of cost.

RAND's previous work found that as the JTRS GMR program devolved, program subcontractors proffered novel, low-cost, partial substitute radio capability outside the prime contractor chain of command.⁴⁰ The existence of these low-cost alternatives contributed to the demise of JTRS. Currently, the question remains whether this outcome was structurally inevitable, a result of a single buyer—the government—attempting to pay a single contractor—Boeing—for an untested capability to be delivered nearly a decade after the initial request.

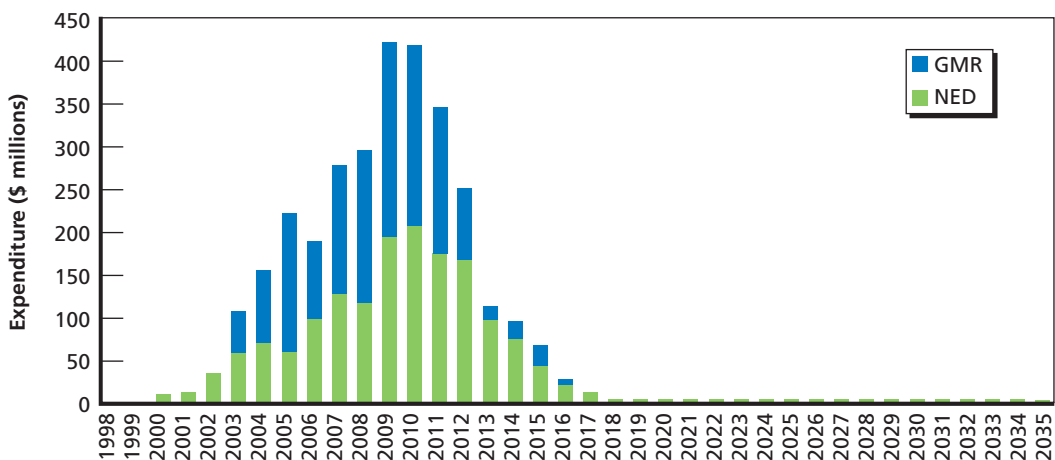
We used cost estimate data reported by the program manager to the Defense Acquisition Management Information Retrieval (DAMIR) system on a yearly basis in the SARs. Given the perturbations of the program structure, where the software and hardware were alternatively part of a single program then part of separate but highly dependent programs, we chose to present cost estimates for the combined GMR-related software and hardware programs that directly pertained to WNW development. Consequently, we combine the RDT&E costs of the GMR and JTRS NED programs and estimate that the total RDT&E cost for the development of JTRS GMR and WNW is \$3.2 billion.

⁴⁰ Harris Corporation offered the PRC-117G in 2011.

The numbers in Figure 1.13 provide data on how much the program estimated it spent per year; it does not illustrate a differential between how much the program thought it would spend in any given year earlier in the program. In fact, in 2002, at the JTRS program baseline, cost estimators placed RDT&E costs for the JTRS hardware at \$845.1 million. By 2011, the estimate for total RDT&E costs for hardware had nearly doubled, to \$1.5 billion (revised to 2002 comparable dollars). Figure 1.14 illustrates this manifestation of cost changes. (One reason for program cancellation included the significant cost increases beyond initial estimation.)

As the total program cost estimates grew for both the hardware and software, managers sought to control expenses by removing originally planned efforts from the program. In 2006, DoD removed two particularly difficult planned hardware instantiations from the program: the Army Aviation Rotary Wing (AARW) and Air Force Tactical Air Control Party (TACP). The sudden drop in 2006 spending, seen in Figure 1.13, reflects this program restructure; however, total cost increases were not stemmed by this move. In the original plan, JTRS program would develop 33 software defined waveforms (32 legacy waveforms and WNW), whereas the final program included only 8.⁴¹

Figure 1.13
JTRS NED and GMR RDT&E Expenditures (Estimate 1)



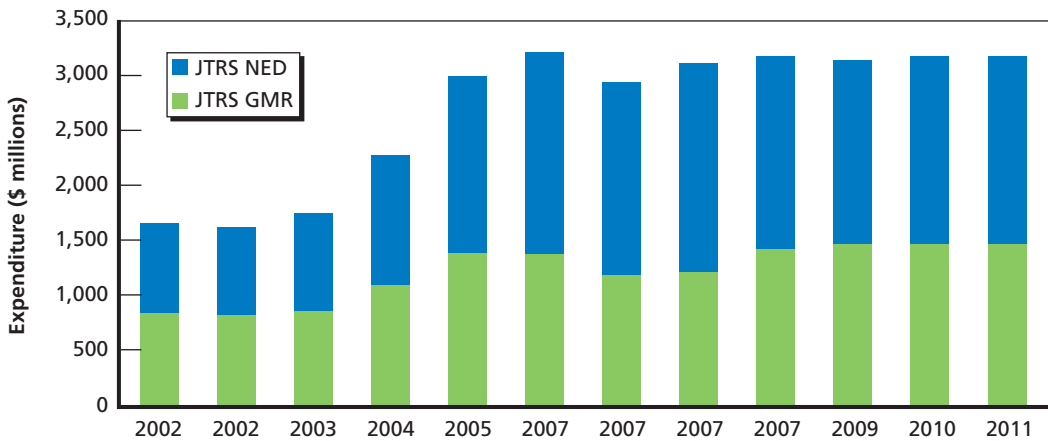
SOURCES: JTRS GMR SAR 12/31/2012. JTRS NED SAR 09/30/2011.

NOTE: Data show actual expenditures through 2011 and projected expenditures after that.

RAND MG1171/5-1.13

⁴¹ General Accounting Office, *Challenges and Risks Associated with the Joint Tactical Radio System Program—Briefing to the House Committee on Appropriations Subcommittee on Defense*, May 5, 2003.

Figure 1.14
JTRS NED and GMR RDT&E Estimated Total Expenditures Over Time (Estimate 2)



SOURCES: JTRS GMR SAR 2002-2011; JTRS NED SAR 2002-2011.

RAND MG1171/5-1.14

LTE Development Costs

To obtain a point of comparison for JTRS/WNW development cost, we estimated how much RDT&E funding was invested globally into developing LTE.

Approach

Since it was impossible to obtain exact data on corporate expenditures for LTE development, we developed an approach that enabled us to make a rough estimate for this key metric based on publicly available information.

We first identified the companies involved in the core activities related to LTE development. We then assessed their product slate and their sales figures and analyzed their patent portfolios. This allowed us to estimate the percentage of each company's business that was LTE-related.

We then researched corporate records to obtain annual RDT&E budgets for these companies, which in combination with the LTE-related share of business allowed us to estimate each company's LTE-related RDT&E expenditures (Figure 1.15).

Step 1: Companies Involved in LTE Development

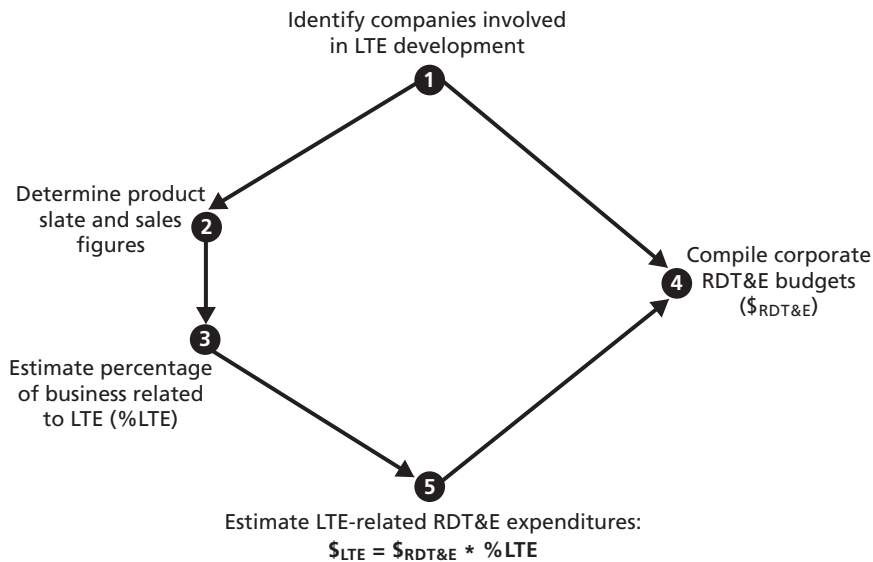
Most companies involved in LTE development were members of the "LTE/SAETrial Initiative" (LSTI) that was active from May 2007 to January 2011.⁴² LSTI was an "open initiative" of equipment vendors and operators and its objective was to "drive industrialization of 3GPP LTE/SAE technology, demonstrate LTE/SAE capabilities against [. . .] requirements, [and] stimulate development of the LTE/SAE ecosystem."⁴³

LSTI was founded by Alcatel-Lucent, Ericsson, Nokia, Nokia Siemens Networks, Nortel, Orange, T-Mobile (Deutsche Telekom), and Vodafone. By 2009, when the

⁴² "LSTI Job Complete," 3GPP homepage, 2011.

⁴³ "An Update from the LTE/SAE Trial Initiative," slide presentation, January 26, 2009.

Figure 1.15
Process for Estimating Industry Expenditures for LTE Development



first commercial deployment of an LTE network took place,⁴⁴ LSTI had grown to 32 members,⁴⁵ which were active in business areas including component manufacturing, infrastructure development, services, testing, handset manufacturing, and commercial mobile service providers (CMSPs). Our analysis focuses on these members, listed in Table 1.2. Note that Nortel filed for bankruptcy in 2009, and T-Mobile is owned by German company Deutsche Telekom. Ericsson was involved in handset manufacturing through Sony Ericsson, from 2001 to 2012.

Steps 2 and 3: Share of Business Related to LTE

Most of the companies listed in Table 1.2 have multiple lines of business, and some are global conglomerates dealing in a variety of goods and services. To estimate the share of each company's business that is actually related to LTE, we looked at product slates and associated sales figures where available, which we obtained from business intelligence databases. We also analyzed patents filed by each company to determine what share of patents—and thus, by extension, of development work—was related to LTE.

⁴⁴ Phil Goldstein, "TeliaSonera Launches First Commercial LTE Network," *FierceWireless*, December 14, 2009.

⁴⁵ Julius Robson, "The LTE/SAE Trial Initiative: Taking LTE/SAE from Specification to Rollout," *IEEE Communications Magazine*, April 2009.

Table 1.2
Members of LSTI

Company	Country	LSTI Member		Sector					
		2007	2009	Compo- nents	Infra- structure	Services	Testing	Hand- sets	CMSP
Alcatel-Lucent	France	x	x		x	x			
Ericsson	Sweden	x	x		x			x	
Nokia & Nokia Siemens Networks	Finland	x	x		x	x		x	
Nortel	Canada	x	x		x				
Orange (France Telecom)	France	x	x						x
T-Mobile (Deutsche Telekom)	United States/ Germany	x	x						x
Vodafone	United Kingdom	x	x						x
China Mobile	China (PRC)		x						x
Huawei	China (PRC)		x		x			x	
Samsung	South Korea		x	x				x	
Agilent	United States		x				x		
Azimuth Systems	United States		x				x		
Freescale	United States		x	x					
Fujitsu	Japan		x	x					
LG Electronics	South Korea		x					x	
Motorola	United States		x	x	x			x	
NEC	Japan		x	x	x	x			
Nethawk (EXFO)	Canada		x				x		
NTT DoCoMo	Japan		x						x
Panasonic	Japan		x	x					
Qualcomm	United States		x	x					
Rohde & Schwarz	Germany		x				x		
SFR	France		x						x
Signalion	Germany		x				x		
SK Telecom	South Korea		x						x
Starent Networks	United States		x		x				
ST-NXP	Switzerland		x	x					
Tektronix	United States		x				x		
Telecom Italia	Italy		x						x
Telefonica	Spain		x						x
ZT	China (PRC)		x					x	

Product Slates and Sales Figures

The primary source for each company's product slate and sales figures was "Hoover's Company Records," which we accessed through RAND's subscription to the "Lexis-Nexis Company Dossier" service. Data for some companies that were not covered in Hoover's were obtained from other sources: the "Corporate Affiliations" database for ZT, "OneSource" for Starent, and "Creditreform" for Signalion. These databases were also accessed through Lexis-Nexis. Product slates for SFR and France Telecom Orange were determined from company websites. The databases and websites were queried in late April and early May 2012, and the results reflect the status as of that time. Figure 1.16 shows an example of an entry from Hoover's, including sales figures and a listing of the business categories in which the company is active.

We used sales figures, where available, to approximate each company's share of wireless-related business and the business categories that it was active in. We used the Hoover's database (and other corporate business activity databases for specific companies that could not be found in Hoover's) to estimate the percentage of the individual companies' business that related to wireless telecom. If such information was not available in Hoover's or the other corporate databases, we used 50 percent. For most of the large players in the business wireless telecom business, the required information was available in Hoover's. Such data were not available for a few firms, mainly smaller foreign companies. In that case, we used 50 percent to estimate (1) the percentage of their business focused on wireless telecom and (2) the percentage of their wireless R&D funds used for wireless telecom R&D. For these relatively small firms, we believe that these estimates are reasonable because even though they are small firms, they are still members of 3GPP. It requires substantial resources to gain entry and participate in the consortium. In addition, member companies are expected to provide technical experts for working committees that meet several times a year in various locations around the world. A small firm that offered only a few products in the wireless telecom space and which did most of its business in other market categories would be unlikely to become a member of the consortium. We realize that there is some error with the 50 percent figure for a few 3GPP firms, but we believe that it represents a reasonable lower bound for the R&D costs of smaller firms that participate in the wireless telecom industry. The resulting percentages are listed in Table 1.3.

Patent Analysis

To obtain a second estimate for the share of a company's business devoted to LTE, we examined the share of LTE-related patents that each company filed during the time period under analysis, using data from ETSI's Intellectual Property Rights (IPR)

Figure 1.16
Screenshot of Company Entry in Hoover's
Business Intelligence Database

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Hoover's Company Records - In-depth Records

April 24, 2012

Telefonaktiebolaget LM Ericsson

Torshamnsgatan 23, Kista
 Stockholm SE-164 83
 Sweden

***** COMMUNICATIONS *****

TELEPHONE: +46-10-719-0000
 URL: <http://www.ericsson.com>

***** COMPANY IDENTIFIERS *****

TICKER: ERIC, ERIC
 HOOVER ID: 41776

***** COMPANY INFORMATION *****

LEGAL STATUS: Public

EMPLOYEES: 104,525
 ONE YEAR EMPLOYEE GROWTH: 16.1%

FT Global 500 (June 2011) RANKING: 188

***** EXECUTIVES *****

OFFICER	TITLE	AGE	SALARY	BONUS	TOTAL_COMPENSATION
Leif Johansson	Chairman	40	-	-	-
Hartvig Wallenberg	Deputy Chairman	54	-	-	-
Svecker Martin-Lof	Deputy Chairman	49	-	-	-

on 4/23/2012 10:00 AM. [View Full Report](#)

Swanberg, who resigned to become chairman of BP.

HOOVER INDUSTRIES:

- [Telecommunications Equipment Manufacturing](#)
 - [WIRELESS TELECOMMUNICATIONS EQUIPMENT MANUFACTURING](#)
 - [Wireless Switching & Transmission Equipment Manufacturing](#)
 - [Wireless Telephone Handset Manufacturing](#)
 - [Wired Telecommunications Equipment Manufacturing](#)
 - [Copper-Wire Switching & Transmission Equipment Manufacturing](#)
 - [Enterprise Telecommunications Equipment Manufacturing](#)
 - [Optical Switching & Transmission Equipment Manufacturing](#)
- [Control, Electromedical, Measuring & Navigational Instruments Manufacturing](#)
 - [Search, Detection, Navigation & Guidance System Manufacturing](#)

***** OFFICE *****

Office	Total
	100

• 2010 Sales

	% of total
Networks	55
Services	39
Multimedia	6
Total	100

COMPETITORS:

- [Alcatel-Lucent](#)
- [Huawei Technologies](#)
- [Nokia Siemens Networks](#)
- [Accenture](#)
- [Amdocs](#)
- [Cisco Systems](#)

SOURCE: Lexis-Nexis Company Dossier, Hoover's Company Records, April 2012. Reprinted with permission from Dun & Bradstreet.

RAND MG117115-1.16

Table 1.3
LTE-Related RDT&E Expenditures for LSTI Members (in U.S. \$ Millions)

Company	Country	RDT&E Spending 2005–2011	Based on Product Slate		Based on Total Patents		Based on Original Patents	
			LTE Share	LTE RDT&E	LTE Share	LTE RDT&E	LTE Share	LTE RDT&E
Alcatel-Lucent	France	22,086	20%	4,420	39%	8,610	47%	10,380
Ericsson	Sweden	29,555	30%	8,870	65%	19,210	66%	19,510
Nokia & Nokia Siemens Networks	Finland	49,882	20%	9,980	35%	17,290	33%	16,290
Nortel	Canada	4,106	17%	700	15%	620	0%	0
Orange	France	7,952	25%	1,990	0%	0	0%	0
T-Mobile (Deutsche Telekom)	United States/ Germany	4,285	50%	2,140	31%	1,330	0%	0
Vodafone	United Kingdom	2,908	44%	1,280	0%	0	0%	0
China Mobile	China (PRC)	*	50%	*	0%	*	0%	*
Huawei	China (PRC)	9,870	14%	1,350	4%	370	1%	70
Samsung	South Korea	28,736	13%	3,660	14%	4,110	42%	11,930
Agilent	United States	2,607	6%	160	0%	0	0%	0
Azimuth Systems	United States	*	6%	*	0%	*	0%	*
Freescale	United States	3,552	8%	300	0%	0	0%	0
Fujitsu	Japan	10,994	4%	470	0%	0	0%	0
LG Electronics	South Korea	5,250	16%	840	33%	1710	39%	2,040
Motorola	United States	6,954	25%	1,740	0%	0	0%	0
NEC	Japan	13,303	10%	1,260	30%	3,960	47%	6,280
Nethawk (EXFO)	Canada	141	13%	20	0%	0	0%	0
NTT DoCoMo	Japan	5,064	50%	2,530	40%	2,000	64%	3,250
Panasonic	Japan	24,413	13%	3,050	55%	13,350	56%	13,700
Qualcomm	United States	10,722	25%	2,680	11%	1,210	11%	1,170
Rohde & Schwarz	Germany	1312	17%	220	0%	0	0%	0
SFR	France	369	25%	90	0%	0	0%	0
Signalion	Germany	*	50%	*	0%	*	0%	*
SK Telecom	South Korea	882	42%	370	0%	0	0%	0
Starent Networks	United States	16,304	50%	8,150	0%	0	0%	0
ST-NXP	Switzerland	7,386	19%	1,380	0%	0	0%	0
Tektronix	United States	1,048	5%	50	0%	0	0%	0
Telecom Italia	Italy	3,912	10%	390	0%	0	0%	0
Telefonica	Spain	4,264	5%	210	0%	0	0%	0
ZT	China (PRC)	*	13%	*	0%	*	0%	*
Total		277,857		58,300		73,770		84,620

NOTE: An asterisk indicates that no data were available.

database.⁴⁶ This database contains a public record of all patents or other expressions of IPR reported or declared to ETSI, including IPR declared with patent offices from 92 different countries. An example entry from the database and its associated information is shown in Table 1.4.

For each LSTI member firm, we calculated the LTE-related share of total patents and original patents issued from 2005 to 2011. An LTE “total patent” refers to a patent that was originally declared for the 3GPP Release 5 standard and declared for LTE at a later date. In comparison, an LTE “original patent” refers to a patent where the declaring company indicated at the start that LTE was the primary applicable standard for the patent. As one can tell, most patents in this field have applications to many different communications standards, and, as a result, companies list all the different standards applicable for each patent.

For the purposes of our calculations, the LTE-related share of total patents and original patents issued from 2005 to 2011 served as a proxy for the share of a company’s RDT&E expenditures associated with LTE. The resulting percentages are listed in Table 1.3 as well.

Step 4: Corporate RDT&E Budgets

Most LSTI member companies are publicly traded and thus published annual financial reports during the period under analysis. If these companies traded on U.S. exchanges, the data were crosschecked using their annual Form 10-K Securities and Exchange Commission (SEC) filings.⁴⁷ These reports included each company’s RDT&E spending. Most of these reports provided figures in U.S. dollars; for those that did not, the amounts were converted into U.S. dollars using the exchange rates for the end of the respective year. Note that the amounts are not adjusted for inflation.

Table 1.4
Example ETSI Database Entry

Patents	Publication	Title	Patent Offices	Declarations
US20080007516	US2009179755 A1	Overload control method	US (United States)	ISLD-200911-002
Declaration Date	Patent Families	Companies	Standards	ETSI Projects
10/27/2009	US20080007516	ALCATEL-LUCENT	TS 136 423 v8.7.0	LTE

⁴⁶ ETSI is an independent, nonprofit organization that is recognized by the European Union as a European Standards Organization. The ETSI IPR database contains data on IPRs “which have been notified to ETSI as being essential, or potentially essential, to ETSI Standards and Technical Specifications.” See “ETSI IPR Database,” ETSI homepage, 2011.

⁴⁷ Both the Annual Reports (financial performance) and the Form 10-K annual filings to the SEC are available at each company’s respective website. Form 10-K annual filings are also available on the SEC EDGAR database. (See “EDGAR Database,” U.S. Securities and Exchange Commission, 2012. Copies of these reports and filings are also kept on file at RAND.

RDT&E expenditures were recorded for 2005 to 2011 for founding members of LSTI and for 2008 to 2011 for members that joined later. The results are listed in Table 1.5.

Four companies—Chinese firms Huawei and ZT, Azimuth Systems from the United States, and the German company Signalion—are not publicly traded and thus no budget information was available for them, and none is included in Table 1.5. However, at least some of these companies can be expected to have invested in RDT&E; thus, the grand total given in the table does not include any RDT&E for these four companies and is, therefore, a conservative estimate.

Step 5: Results

Multiplying the percentages determined in Step 3 with the overall RDT&E budgets for each company determined in Step 4 yields three different estimates for the LTE-related RDT&E expenditures of the companies included in this analysis, ranging from approximately \$58 billion to \$85 billion (U.S. dollars), as indicated in Table 1.3. Figure 1.17 shows the distribution of estimated LTE development cost across the LSTI members, ranked from highest to lowest contributor, and excluding China Mobile, Azimuth Systems, Signalion, and ZT since, as mentioned above, no data were available for these companies. The figure also shows the estimated percentage of LTE-related RDT&E, based on the product slate approach, for each company.

Accounting for Competition and Redundancy

It could be argued that industry invested more in LTE development than would have been necessary, since, as shown in Table 1.6, multiple companies cover each business sector, and this redundancy led to parallel development efforts and thus increased expenditures. To take this into account and to allow for a more accurate comparison with the cost of WNW development, we developed a “redundancy factor” by which to adjust the estimated cost.

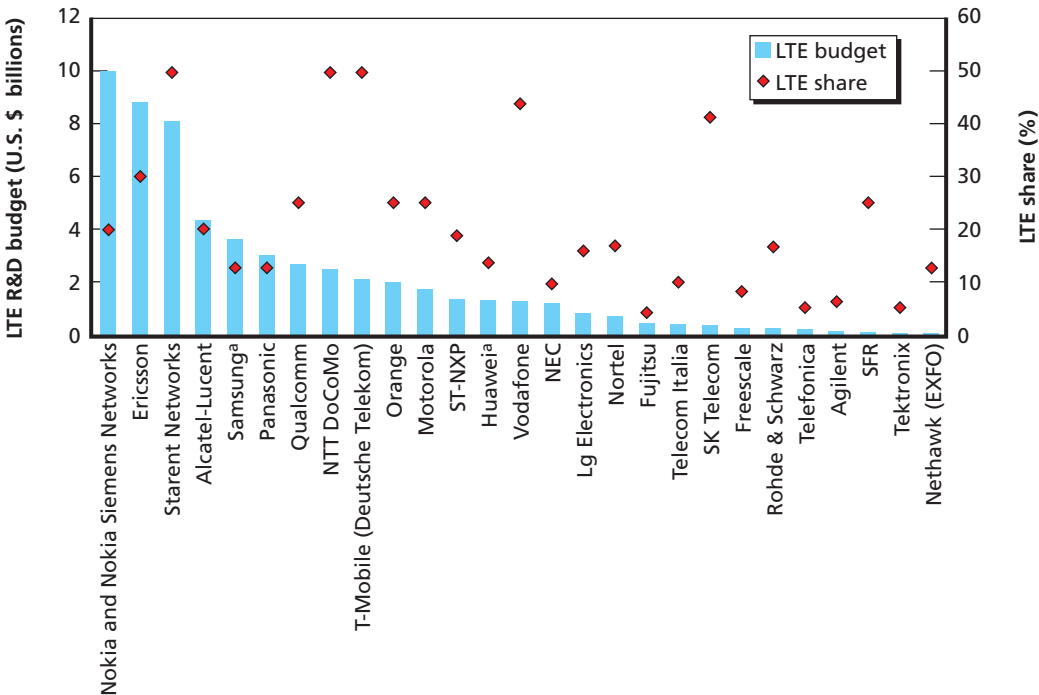
Using the allocation of companies to business sectors provided in Table 1.2, we counted how many companies were active in each sector and then divided this number by a desired redundancy value. We set this value at four, indicating that four competitors in a given sector are the minimum number required to foster healthy competition and guard against the creation of monopolies through mergers. We used four as the minimum number of firms in a market to define the redundancy factor in our analysis because it relates directly to a key metric used in antitrust analysis from the economics literature. This is the command, control, computers, and communications (C4) factor, which measures market concentration or power of the four largest firms in a market. For example, a C4 of 100 percent indicates monopoly conditions. A C4 over 60

Table 1.5
Corporate RDT&E Budgets for Period of Interest

Company	Country	LSTI Member		RDT&E Expenditures (U.S. \$ Millions)								Total 2005– 2011
		2007	2009	2005	2006	2007	2008	2009	2010	2011		
Alcatel-Lucent	France	x	x	1,537	1,934	4,348	3,886	3,731	3,449	3,201	22,086	
Ericsson	Sweden	x	x	3,077	4,012	4,498	3,979	4,604	4,658	4,727	29,555	
Nokia & Nokia Siemens Networks	Finland	x	x	4,530	5,141	8,295	8,412	8,469	7,769	7,266	49,882	
Nortel	Canada	x	x	*	*	1,723	1,573	703	107	0	4,106	
Orange	France	x	x	848	1,129	1,316	1,269	1,235	1,120	1,035	7,952	
T-Mobile (Deutsche Telekom)	United States/ Germany	x	x	592	660	856	826	628	408	315	4,285	
Vodafone	United Kingdom	x	x	341	403	467	339	446	469	443	2,908	
China Mobile	China (PRC)		x				*	*	*	*	*	
Huawei	China (PRC)		x				1,527	1,951	2,669	3,723	9,870	
Samsung	South Korea		x				5,609	6,485	7,989	8,653	28,736	
Agilent	United States		x				704	642	612	649	2,607	
Azimuth Systems	United States		x				*	*	*	*	*	
Freescale	United States		x				1,140	833	782	797	3,552	
Fujitsu	Japan		x				2,764	2,438	2,896	2,896	10,994	
LG Electronics	South Korea		x				1,374	1,089	1,323	1,464	5,250	
Motorola	United States		x				2,358	1,591	1,479	1,526	6,954	
NEC	Japan		x				3,896	3,756	3,384	2,267	13,303	
Nethawk (EXFO)	Canada		x				27	28	38	48	141	
NTT DoCoMo	Japan		x				1,216	1,092	1,347	1,409	5,064	
Panasonic	Japan		x				6,135	5,614	5,847	6,817	24,413	
Qualcomm	United States		x				2,281	2,995	2,451	2,995	10,722	
Rohde & Schwarz	Germany		x				339	343	319	312	1312	
SFR	France		x				89	100	93	87	369	
Signalion	Germany		x				*	*	*	*	*	
SK Telecom	South Korea		x				190	207	234	251	882	
Starent Networks	United States		x				0	5,208	5,273	5,823	16,304	
ST-NXP	Switzerland		x				319	2,365	2,350	2,352	7,386	
Tektronix	United States		x				262	216	258	312	1,048	
Telecom Italia	Italy		x				989	1,207	925	791	3,912	
Telefonica	Spain		x				942	993	1,056	1,273	4,264	
ZT	China (PRC)		x				*	*	*	*	*	
Total		7	31	10,925	13,279	21,503	52,445	58,969	59,305	61,432	277,857	

NOTE: An asterisk indicates that no data were available.

Figure 1.17
Estimated LTE Development Cost and LTE Share of RDT&E Investments by Company



NOTE: No financial data were available for China Mobile^a, Azimuth Systems, Signalion, and ZTE.
^a Permanent and elected members of LSTI's Steering Board for 2009.

RAND MG1171/5-1.17

percent indicates oligopoly. We realize that economists use other, more detailed metrics to measure market concentration such as the Hirschman-Herfindahl Index, but these other metrics would require much more analysis to apply in our case.⁴⁸ The C4 metric, on the other hand, can be applied directly to our data set. In the text, we have added a discussion of this issue and a citation that provides an explanation of the C4 metric. Table 1.6 shows the resulting redundancy factor values for each sector.

Table 1.6
Redundancy Factors for Each Business Sector

Business Sector	Components	Infrastructure	Services	Testing	Handsets	CMSP
LSTI members active in sector	8	8	3	6	7	9
Desired number of competitors			4			
Redundancy factor for sector	2.0	2.0	1.0	1.5	1.8	2.3

⁴⁸ Janice Hauge and Mark Jamison, *Analyzing Telecommunications Market Competition: Foundations for Best Practices*, Gainesville, Fla.: Public Utility Research Center, University of Florida, October 29, 2009.

The redundancy factors for each sector were averaged, resulting in an overall redundancy factor of 1.75 by which to divide the cost estimates provided above. Using this approach, the idealized LTE-related RDT&E investment cost to be used for comparison with WNW development cost ranges from \$33 billion to \$48 billion (U.S. dollars).

We also performed an additional estimation to bound our estimate, using 5 percent as an arbitrary lower limit for the average LTE-related share of a company's RDT&E budget, which resulted in total LTE-related RDT&E expenditures of approximately \$14 billion (U.S. dollars).

These estimates indicate that industry invested significantly in LTE development over the period 2005 to 2011.

Caveats

The estimation process we developed relies on several assumptions that limit the accuracy of the results. As is evident from the descriptions above, our estimations for the LTE-related share of a company's business are rough approximations. Furthermore, a company's product slate and involvement in LTE development may have changed over the years, but we had only 2012 Hoover's data available. In particular, Nortel's bankruptcy in 2009 influenced that company's activities. For some companies, only limited data were available, and no RDT&E investment figures were available for four privately held companies. Finally, we did not attempt to capture the expenses of companies that were not members of LSTI but may have made contributions to LTE development nevertheless.

Summary

The results of the cost analysis presented in this chapter are summarized below. We remind the reader that we did not have access to original source data from LTE developers because private industry firms typically do not break out how they spend R&D funds. For that reason, we had to estimate LTE development costs using publicly available information. On the other hand, because LTE development was led by 3GPP and because 3GPP identified the firms that participated in LTE development, we know who these private firms are.

We developed LTE R&D estimates using three approaches: (1) by estimating the R&D costs for LTE as a percentage of the total R&D costs for all products produced by each firm, (2) by estimating LTE development costs on the basis of original patents issued to individual firms for LTE intellectual products, and (3) by estimating LTE development costs on the basis of the total patents issued to each firm involved in the development of LTE. The results of these three different estimating techniques are shown in Table 1.7.

We also estimated LTE RDT&E costs using the product slate-based approach but using the very conservative assumption that only 5 percent of the publicly announced

Table 1.7
Total LTE/SAE Costs (2007–2011)

Estimation Approach	LTE RDT&E Expenditures (U.S. \$ billions)
Product slate-based	58
Optimistic (5%)	14
Original patent shares	85
Total patent shares	85

RDT&E funds each firm expended were devoted to LTE. We characterize this as the “optimistic (5%)” cost estimate approach. Using this approach, we estimate that total worldwide LTE RDT&E costs were approximately \$14 billion (U.S. dollars).

It was much easier to estimate GMR and WNW RDT&E costs using cost data from JTRS program offices. Those results are given in Table 1.8, which shows that the total GMR and WNW RDT&E costs were approximately \$3.2 billion (U.S. dollars).

The results shown in Tables 1.7 and 1.8 indicate that LTE/SAE RDT&E costs are substantially greater than those for GMR and WNW, regardless of the method chosen to estimate these costs.

LTE RDT&E costs were a factor of 4 to 24 times greater than those for GMR and WNW, which raises the question as to whether the DoD did not expend enough funds on R&D to reduce the technical risks associated with JTRS GMR and WNW development.

Conclusions

This study examined the technical performance capabilities, development costs, and organizations that led to the development of the LTE and JTRS GMR WNW communication networking systems. Below, we summarize the major findings of this study.

Table 1.8
Total GMR & WNW Costs (2002–2011)

Program	GMR and WNW RDT&E Expenditures (U.S. \$ billions)
GMR	1.5
JTRS NED	1.7
Total	3.2

Findings

When comparing the JTRS GMR WNW program with LTE, four issues stand out. First, the amount spent on JTRS GMR and WNW RDT&E appears to be far less than was needed when compared to the amount spent for RDT&E by commercial firms in the development of LTE. Second, the more evolutionary development approach for LTE along with the higher RDT&E expenditure enabled project personnel to deal with system performance and technology risk issues as they came up. Third, the JTRS program structure that separated hardware and software development coupled with a “big bang” acquisition approach (the delivery of a system that could meet all requirements at Milestone C) not only complicated coordination needs among programs but also may have delayed the discovery of integration problems until it was too late or too near Milestone C. And last, the IP model used in the DoD JTRS program may have prevented the incorporation of needed technologies into the program that could have reduced technical risks and performance issues. In contrast, the more inclusive 3GPP IP model encouraged the incorporation of a worldwide and world-class set of technology IP into LTE. We elaborate on these issues below.

Organizations and Intellectual Property Rights

Although the two systems differ significantly in technical and design aspects, they share common underlying wireless communications technologies.

The organizational structures that spearheaded the development of these two systems are quite different. Furthermore, the LTE and GMR WNW development approaches and architecture are significantly different. The LTE architecture is not software-defined, and hardware components (microchips in particular) are shared between collaborating vendors but software developed by competing commercial vendors is not. IP rights to LTE software are retained by individual vendors in most cases. In comparison, JTRS GMR-WNW architecture is software-defined: The software is government-owned and can be shared between vendors, if approved by the government, whereas GMR hardware is not shared outside the original development team of contractors.

The organizational model and technology-sharing rules differ substantially in the two approaches. JTRS GMR WNW was developed in a traditional DoD acquisition program with IP access controlled by a select number of program contractors and government personnel. IP for executable software code is retained by the government, whereas IP for hardware designs is retained by individual contractors. The GMR WNW system was developed by two acquisition programs, one responsible predominantly for hardware development and for the OS software for the hardware platform (the GMR program) and other responsible predominantly for only software for WNW (the JTRS NED program). One complication of this arrangement is that a significant amount of coordination was required between the two programs for software development. The JTRS JPEO was responsible for coordinating and aligning products of the

GMR and NED programs. One mechanism used to effect the coordination of software development efforts was the development of a set of software standards for JTRS program radios—the SCA.

In comparison, the LTE/SAE architecture is specified by a set of technical standards that was developed by the 3GPP international consortium. The consortium's governing body is a global set of regional telecommunications standards-setting organizations. 3GPP also includes industry firms. LTE/SAE standards are developed by industry experts from member firms. Individual firms have the option to offer their own IP to form a part of one or more LTE/SAE standards. If accepted by the group, this IP is then available to other 3GPP members to use in their own products under the terms of the 3GPP essential patent-licensing policy. IPR are retained by the individual 3GPP member firms, but licenses for essential LTE/SAE patents must be made available to other 3GPP member firms on a fair, reasonable, and nondiscriminatory basis.

Development Costs

One of the most surprising results of this study concerns RDT&E costs. Significantly more funds were expended for the development of LTE than was allocated by the DoD for the development of JTRS GMR WNW. We note that some of the difference may stem from redundant investments by industry competitors, but we tried to take into account this effect in our cost analysis methodology. LTE RDT&E costs were at least a factor of four greater than those for GMR and WN and were more likely to be a factor of 10 to 24 times greater.

This finding raises the question as to whether the DoD did not make a large enough R&D investment to reduce the substantial technical risks associated with the advanced technologies needed for this program.

Of course, JTRS is not the only DoD program that has suffered significant cost growth over the past decade. And perhaps what has been observed with JTRS is just symptomatic of a larger issue within the DoD, where cost estimation processes lead to overly optimistic and ultimately unrealistic cost estimates for DoD acquisition programs that require the development of advanced technologies.

Development Time Lines and Approaches

The development time lines overall for JTRS GMR WNW and for LTE are comparable. Initial requirements development for the GMR program took approximately six years compared to about five years for LTE. On the other hand, system development took nine years for JTRS GMR and WNW and only six years for LTE. One reason for the significant difference in the latter time line is that there was more concurrent development of requirements and systems in the LTE program.

WNW and LTE share common technologies in radio frequency modulation schemes, but LTE incorporates some advanced technologies not available in WNW such as MIMO and use of multiple antennas in handsets and eNode B radio access network nodes. LTE also employs a new power-efficient, high-performance, an uplink

waveform and wider bandwidth downlink channels than are available in WNW. The LTE network architecture has demonstrated that it is scalable and can support over 1,000 nodes in a single wireless network.

LTE and WNW network and security architectures are substantially different. JTRS WNW is a single-tier, peer-to-peer network where each node is identical and has all the necessary intelligence built into it so that it can function effectively even on the move as part of a MANET. As field tests have shown, WNW network scalability has not been demonstrated beyond 30 nodes. In contrast, the LTE/SAE network architecture is based on a two-tier network where a single radio access point (eNode B) can support over 1,000 wireless nodes. Finally, both network architectures have yet to fully integrate voice and data communications (although 3GPP is developing plans and standards for this integration in future releases of the LTE set of standards).

The development approaches for the two initiatives also differ significantly. The JTRS program approach initially called for the development of an entirely new MANET communications architecture that relied on a number of new and unproven technologies. In other words, it used a “big bang” type of an approach where it was assumed that an entirely new system could be developed and that the new technologies needed to make the system work could be developed concurrently with the system itself. Later, after the program had encountered significant cost, performance, and schedule problems, the program’s organizational approach was changed significantly. In the restructured program, hardware and software development were separated into separate programs. It is debatable whether this new organizational approach was a success.

On the other hand, the LTE development approach was decidedly different. As its name suggests, private industry and 3GPP took an evolutionary approach toward the development of this new system architecture. LTE represents an incremental development approach for next-generation wireless cellular communications networks. Just as in current 3G wireless networks, voice and data backhaul networks are separated in the initial versions of LTE. It was judged to be too difficult to integrate them along with all the other architectural changes that were made in the initial versions of the LTE network architecture. In these initial versions, development emphasis was placed on improving the spectral efficiency and performance of the radio access network, on consolidating the number of network nodes needed in the backhaul network, and finally on transitioning the backhaul network to a standard IP-based network. And perhaps most important, the fundamental two-tiered structure of current wireless cellular networks was preserved in LTE. In this two-tiered structure, the connection between the two LTE network tiers is provided by the eNode B network node, which remains fixed. This is in contrast to the MANET network designs that were developed as part of the JTRS GMR and WNW programs, in which no network nodes have to remain stationary. The evolutionary approach taken in the LTE development enabled the LTE network to scale up to thousands of wireless nodes; in contrast, the MANET design

developed for GMR and WNW number was never able to scale up to such large network sizes. The technology needed to do this remains to be developed.

Program Outcomes

It is important to consider the outcomes of these two development efforts. The JTRS GMR WNW development effort lasted for approximately 12 years and has not yet resulted in a product fielded to the U.S. Army. The GMR program was canceled in 2011, and the JTRS program responsible for the development of WNW was restructured in 2012 and is now called the JTNC. The JTNC will be responsible for the continued development of JTRS waveforms and will assume the responsibility for transitioning these waveforms (including WNW) to commercial radios (radios developed by defense contractors using their own internal R&D funds). So in terms of hardware development efforts, the JTRS GMR program was not a success as it did not lead to fielded hardware products. However, the waveform development part of the JTRS family programs (JTRS NED) was somewhat more successful and led to the development of advanced networking waveforms that may be used in future commercial radios whose initial versions have already been fielded to U.S. Army and Marine Corps units.

Recommendations

Our analysis shows that in hindsight, GMR and WNW development costs do not appear to be exorbitant given the challenging requirements originally established for the JTRS program, and perhaps the DoD did not invest enough in upfront R&D to reduce WNW technical risks. If WNW is to be scaled up to larger networks of 100 nodes or more, additional RDT&E funds will be necessary. Such an R&D program could be carried out by JTNC, or by the Army's Research, Development and Engineering Command, using commercial radios, when they become available.

Another possible approach will be necessary if the Army and DoD decide that WNW cannot meet future warfighter needs. If this is the case, given the limited R&D dollars likely to be available in future budgets, the DoD should consider adapting LTE to meet its operational and security needs. In this case, a new DoD R&D investment strategy will be needed that leverages best practices from the commercial sector, including the use of technical standards, to foster collaboration among competing defense contractors. Such an approach for the DoD would be new but could leverage the model established by 3GPP.

In any case, alternatives to the JTRS development approach based on software-defined radios and waveforms should be considered in future DoD communications systems developments. The JTRS SCA is aging quickly in a world of rapidly changing software architecture standards and may no longer provide the best standards platform for radio development. Furthermore, it is not consistent with recent industry trends toward tighter integration of software and hardware. A technical standards-based approach that also incorporates provisions for licensing essential patents at fair

and reasonable prices and in a nondiscriminating fashion should be core tenets of this new R&D strategy.

In addition, alternatives to the standard DoD acquisition process should be sought out for DoD IT and communications system programs. DoD IT and communications should follow the LTE development model and pursue an evolutionary approach. Such an approach is possible if essential patents for current and future (evolved) systems can be licensed in a fair and nondiscriminatory basis with competing contractors. The DoD should also initiate such programs with a new standards development phase that enables a broad cross-section of industry to contribute and share patents deemed essential for system development. The DoD should also consider altering later program phases to enable broader industry competition that such an IPR-sharing approach will enable.

Finally, the DoD should cast a wider technology net to incorporate the latest commercially developed advanced information technologies. To do this, the DoD should consider joining 3GPP and explore the option of enabling 3GPP common essential patents to be used in military systems.

Multiple Nunn-McCurdy Breaches

The Performance Assessments and Root Cause Analysis (PARCA) office asked RAND to review programs that had breached Nunn-McCurdy thresholds with the main objective of understanding how these program breaches evolved. We were asked the following three research questions:

- Are programs that have a Nunn-McCurdy breach more likely to breach again?
- What can we learn from the cost growth trends of those programs that have had multiple Nunn-McCurdy breaches?
- What can we learn from the management actions taken on programs with multiple breaches? Are there common issues that were missed at the first breach?

Analytical Approach

We used a two-phased analytic approach for this exploratory research. In the first phase of this research, we addressed the first two questions. We tried to understand the trends in unit cost growth for the programs with multiple breaches. We also compared the relative numbers of programs that experience single breaches with those that had multiple breaches. In the second phase, we explored issues of programs with repeat Nunn-McCurdy breaches, focusing on what was missed at the initial breach and how management actions evolved.¹ We used case studies of four programs to perform this second phase.

Because we had limited resources for this research effort, we focused on a readily available data source for our research—the SARs. Although there are limitations in using these data,² these reports contain the most consistent and readily available data to which we have access for a large cross-section of programs. For the first phase of our

¹ A Nunn-McCurdy breach occurs when the procurement acquisition unit cost (PAUC) or average procurement unit cost (APUC) exceeds certain percentages. See Appendix A for fuller explanations.

² See, for example, Paul G. Hough, *Pitfalls in Calculating Cost Growth from Selected Acquisition Reports*, Santa Monica, Calif.: RAND Corporation, N-3136-AF, 1992.

research, we identified programs (using SARs) reporting Nunn-McCurdy breaches in more than one fiscal year. At this point, we did not sort out programs that may not have had legitimate repeat breaches; however, we were able to plot both a program's breach reporting history and trends in PAUC or APUC. In addition to collecting data on the programs, we also collected any recent analysis of programs with repeated Nunn-McCurdy breaches in the literature.

The data we used came from the Office of the DAMIR system, which allowed us to review data on MDAPs going back to 1997. We extracted the following program details from SARs:

- name (including subprogram)
- acquisition category (ACAT) status
- service (component)
- milestone information (SAR date where data were collected; Milestone II/B, Milestone C/III, and IOC/FUE [initial operating capability/first unit equipped] when available)
- Nunn-McCurdy unit cost metrics provided in the SARs (PAUC and APUC) against current and original baselines. This includes whether the breach was critical or significant and the exact percentage change in base year dollars (BY \$).³

Next, we separated programs that reported more than one Nunn-McCurdy breach during the timeframe of the dataset without looking for any programs that might have reported the same breach over multiple fiscal years. After identifying these programs, we created two sets of plots for each program: breach reporting history and trends in APUC and PAUC. For the APUC and PAUC, we specifically looked at the following percentage changes over time:

- PAUC against the current baseline in BY \$
- APUC against the current baseline in BY \$
- PAUC against the original/revised baseline in BY \$
- APUC against the original/revised baseline in BY \$.

Next, we extracted the explanations that were provided in the SARs for the reported breaches for each individual program. This was the first step in developing an understanding of whether reports over multiple fiscal years for a particular program could be considered as a new breach or just a continuation of the original breach.

After constructing the plots for programs with repeated Nunn-McCurdy breaches, we also constructed tables that plotted the breach history for each program over time. These tables included the SAR reporting years and indicated any critical or significant

³ A breach that exceeds the current budget PAUC or APUC by 15 percent is considered significant, and one that exceeds the current budget by 25 percent is considered critical.

Nunn-McCurdy breaches. This same table provided data on whether the program had a change in its acquisition program baseline (APB) during that same reporting period.

In the second phase of this research, we conducted an exploratory analysis of actions taken during breaches using SARs and Acquisition Decision Memoranda (ADMs) with a focus on four programs:

- Space-Based Infrared System (SBIRS High) (satellite)
- C-130 Avionics Modernization Program (C-130 AMP) (aircraft electronics)
- Joint Primary Aircraft Training System (JPATS) (aircraft training)
- H-1 Upgrades (4BW/4BN) (aircraft).

This second phase attempted to examine what the programs fixed and did not fix after the previous breaches. We then focused on identifying alternatives as to why a program might breach multiple times. These reasons included the following:

- Something new and adverse happened.
- The DoD did not identify the problem or identified the wrong problem at the previous breach.
- The DoD identified the problem that caused cost growth to date but did not recognize how the problem would continue to affect the program in the future.
- The DoD identified the problem but did not take action to address it.
- The DoD identified the problem but the actions taken were ineffective. This could be because the actions taken were insufficient or not persistent.

For this second phase, we collected and reviewed all available SARs and ADMs for these programs and focused on the following details regarding the programs:

- overall program history
- whether a breach occurred during each SAR/ADM reporting period
- main challenges or specific problems that affected the program (e.g., technology, cost, schedule) and possibly led to the breaches
- actions taken before, during, and after breaches using SARs and ADMs
- implementation of solutions for problems that caused the breaches.

Note that this second phase is highly speculative. Because of limits on study funding and the desire not to burden programs, we drew inferences from the program records exclusively from the SARs. We did not discuss these interpretations with anyone (either contractor or government) related to the programs. Thus, we could have a misinformed view as a result of the limited information contained within the SARs.

The remainder of this chapter is broken into three sections. The next section reviews the first phase of this work: the major changes to the Nunn-McCurdy legislation in 2006, counting program breaches, and a summary of the multiple breach sta-

tistics. The section following that provides detailed discussions of the four programs selected for the second phase and examines actions taken. The final section summarizes our observations with respect to the three research questions.

Phase 1: Exploring Multiple Breaches

Changes to the Nunn-McCurdy Legislation

Since the 1980s, the Nunn-McCurdy legislation has undergone several changes. However, one significant change appeared in the fiscal year (FY) 2006 National Defense Authorization Act (P.L. 109-163): Congress directed that cost growth be measured against the original baseline estimate (in addition to the current baseline). As a result of this legislation, more programs had Nunn-McCurdy breaches than otherwise would have been the case under the original act because programs could rebaseline to avoid breaches before this legislation. “According to DOD, 11 programs that did not have a Nunn-McCurdy breach before the new FY2006 requirements were recategorized as having significant breaches as a result of the legislation’s new original baseline.”⁴ Some of the repeat Nunn-McCurdy breaches can be attributed in part to changes in legislation rather than new program issues.

Counting Nunn-McCurdy Breaches

Counting the number of breaches for a program that has multiple breaches is not as straightforward as it might seem on the surface. Several important factors require consideration in identifying programs with multiple breaches:

- Rebaselines and revised APBs can distort the count before 2006;
- Whether transitioning from “significant” to “critical” Nunn-McCurdy breaches counts as separate breaches⁵;
- A program might report a breach for multiple fiscal years until it is restructured;
- Whether the PAUC and APUC breaches are independent or related;
- The change in Nunn-McCurdy law in fiscal year 2006, i.e., the additional reporting requirement that required unit cost to be reported relative to the program’s original baseline⁶;
- How to count programs that may split into multiple programs.

⁴ Moshe Schwartz, *The Nunn-McCurdy Act: Background, Analysis, and Issues for Congress*, Congressional Research Service, January 31, 2011, p. 10.

⁵ A “significant” breach is when the current baseline estimate is breached by 15 percent or the original baseline estimate is breached by 30 percent. A “critical” breach is when the current baseline estimate is breached by 25 percent or the original baseline estimate is breached by 50 percent. See Appendix A for further discussion.

⁶ The requirement to report breaches still exists, and the thresholds are lower than in the original baseline. See Appendix A on the history of Nunn-McCurdy legislation.

RAND Methodology for Counting Multiple Breaches

For this analysis, we tried to take as simple an approach as possible. Once a program breaches either APUC or PAUC (either significant or critical), that counts as a breach. We did not consider that a program going from significant to critical as an additional breach but rather as just a further evolution of the same breach. Likewise, we observed generally that APUC and PAUC were so correlated in terms of breaches, that counting breaches of APUC and PAUC independently did not make sense. Also, if one or the other lags by a year or so, that would not constitute a second breach. For example, if a program had a critical breach in APUC one fiscal year and critical or significant breach in PAUC the following year, we did not count that as two breaches but rather as a single breach. The only time we restarted the counting is when there had been a rebaseline (before 2006) or a recertification.

GAO Methodology for Counting Multiple Breaches

The GAO uses a slightly different methodology. In testimony to Congress in March 2011, Michael J. Sullivan (Director Acquisition and Sourcing Management at the GAO) briefly explained how GAO counted programs with multiple breaches:

To identify trends in Nunn-McCurdy breaches, we collected and analyzed existing data on breaches from DOD's Defense Acquisition Management Information Retrieval system, which contains data on breaches since 1997. DOD officials also provided us with a list of programs that breached the cost growth thresholds since 1997, which we analyzed to remove duplicate entries. In addition, we reviewed analyses by the Office of the Director of Cost Assessment and Program Evaluation to verify our data. We utilized information from SARs for individual weapon systems to explore trends by various program characteristics including military service, type of weapon system, and contractor. To identify factors responsible for trends in Nunn-McCurdy breaches, we reviewed DOD's root cause analyses and analyzed data from SARs, compared breach trends to statutory changes, and summarized our past findings on programs that have experienced breaches. To identify factors responsible for trends and identify changes DOD is making or proposing to make to the Nunn-McCurdy process, we interviewed relevant officials from the offices of the Undersecretary of Defense for Acquisition, Technology, and Logistics; Performance Assessments and Root Cause Analyses; Cost Assessment and Program Evaluation; the Comptroller; and the Joint Staff. We also reviewed DOD policy memoranda and proposed legislation to learn about the current policy and proposed legislative changes.⁷

⁷ Government Accountability Office, *The Honorable Thomas Carper Chairman Committee on Homeland Security and Governmental Affairs Subcommittee on Federal Financial Management, Government Information, Federal Services, and International Security United States Senate Subject: Trends in Nunn-McCurdy Cost Breaches for Major Defense Acquisition Programs*, Washington, D.C., GAO-11-295R, March 9, 2011a, pp. 1–2.

In addition, the GAO considered a breach as a duplicate if the same breach was reported in multiple SARs. They found that “significant” breaches were the most common duplicates.⁸ Finally, the GAO counted breaches from multiple subprograms within one major program as one breach in a given year; and if there were both critical and significant Nunn-McCurdy breaches in the same SAR, then this was also considered one breach.⁹

The GAO published some of the most recent work done on multiple breach programs. In March 2011, it released its report on *Trends in Nunn-McCurdy Breaches and Tools to Manage Weapon Systems Acquisition Costs*. In this analysis of programs with repeat Nunn-McCurdy breaches for PARCA, we used the GAO’s count as a basis of comparison with our own count of the same major weapon system programs during the same time period (since 1997) using a similar source (SARs).

The result of the above methodologies for counting multiple breach programs appears in Table 2.1. Each methodology identifies 18 multiple breach programs since 1997 through SARs; however, the number of breaches varies from program to program. In only five of the 18 programs do both methodologies agree on the number of multiple breaches. This result signifies that identifying multiple breach programs is a challenging task that is subject to differences in interpretation. Unfortunately, we are unable to explain these differences, as we do not have insight into the precise counting method the GAO used.

A few programs merit comment. The SSN 774 program reached a significant breach in the 2002 SAR but was later rebaselined for the 2003 SAR, so that breach went away. However, with the legislative change to Nunn-McCurdy procedures in 2006, that significant breach against the original baseline now reappears. We counted this as a single breach because the two breaches that occurred (and are reported by GAO) are manifestations of the same original growth. Figure 2.1 shows the breach-reporting history for the SSN 774 program. The figure displays the years for which the SARs report a breach, either critical or significant. Significant breaches are indicated by an “S” with a yellow background. Critical breaches are indicated by a “C” with a red background. Breaches are indicated against both baseline criteria (original and current). Before the 2005 SARs, programs were not required to report against the original baseline; hence, this is greyed out in the figure. Years for which the baseline is revised are indicated by blue shading.

The CHEM DEMIL program is difficult to assess because it had two complications: It was split into multiple programs and its breach(es) transitioned across the 2006 change in the Nunn-McCurdy legislation. Because of these issues, it is difficult to make a consistent count (hence the plus signs added to the values, which could be more than shown in the table).

⁸ Government Accountability Office, 2011a, p. 1.

⁹ Government Accountability Office, 2011a, p. 6.

Table 2.1
RAND and GAO Counting of Multiple Breach Programs (1997 Through 2009)

Program	Number of Nunn-McCurdy Breaches	
	RAND	GAO
Advanced extremely high frequency	2	3
Armed reconnaissance helicopter	1	2
Advanced threat infrared countermeasures/common missile warning system	3	3
B-1B conventional missile upgrade program	1	2
C-130 avionics modernization program	2	3
Chemical demilitarization (Chem Demil)/assembled chemical weapons alternatives	2+	
Chem Demil/Chemical Materials Agency (CMA)	1+	3
Chem Demil/CMA Newport	1+	2
Expeditionary fighting vehicle	2	2
F-35	2	3
Global Hawk	2	3
Guided multiple launch rocket system (GMLRS)/GMLRS alternative warhead	2	
H1 Upgrades	2	2
Joint air-to-surface standoff missile	1	2
Javelin	2	2
National polar-orbiting operational environmental satellite system	2	2
SBIRS High	2	4
Nuclear submarine (SSN) 774	1	2

SOURCES: RAND analysis of SAR data from 1997 through 2009 and Government Accountability Office, 2011b, p. 10.

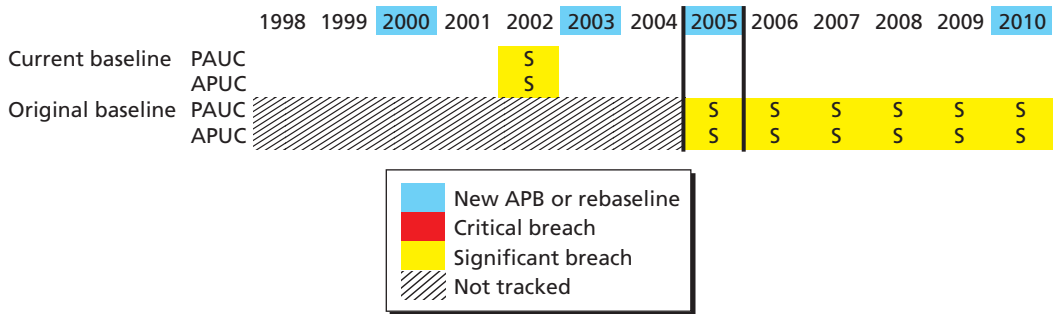
NOTES: A plus sign indicates some uncertainty in counting the number of breaches for the Chem Demil program because the program was split into multiple efforts from a single program. The count could be higher if breaches for the presplit program are included.

Overall Statistics for Multiple Nunn-McCurdy Breach Programs

Using data reported in both annual and quarterly SARs in DAMIR from 1997 through June 2011 on MDAPs,¹⁰ we were able to identify individual programs with one or more Nunn-McCurdy breaches as described above. This produced a sample set of 53 indi-

¹⁰ We excluded programs that started in either 2010 or 2011. These programs would not likely experience multiple breaches because of their limited reporting.

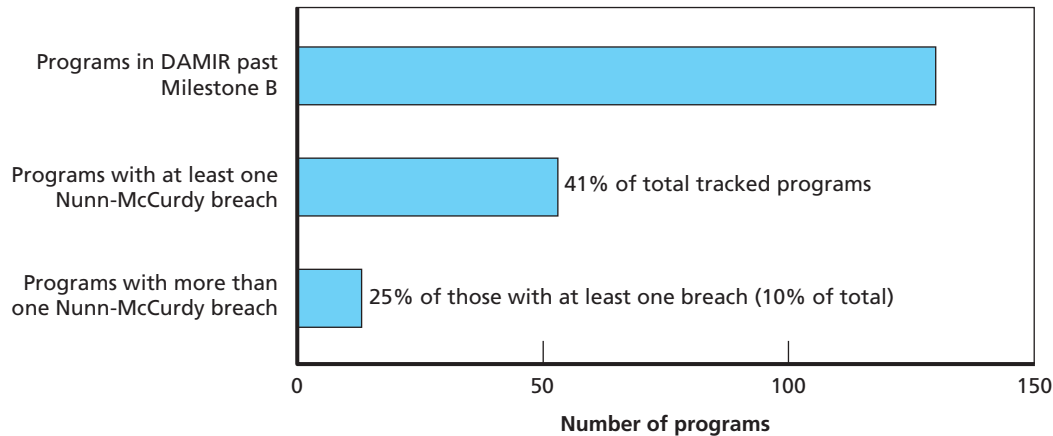
Figure 2.1
SSN 774 Nunn-McCurdy Breach History



RAND MG1171/5-2.1

vidual programs that reported at least one Nunn-McCurdy breach from 1997 through June 2011. We also gathered a complete list of individual programs during that same time period, which gave us the total set of MDAPs at 130 programs excluding programs that started reporting in either 2010 or 2011. We identified 13 programs¹¹ that have had multiple or repeat Nunn-McCurdy breaches. Using the quantities reported above, Figure 2.2 shows the population demographics of MDAPs in DAMIR reporting unit cost measures from 1997 to June 2011. Forty-one percent of the total pro-

Figure 2.2
Populations Demographics (Based on DAMIR Since 1997)



SOURCE: Data extracted from SARs (1997 through 2009).

NOTE: A list of the programs appears in Appendix B.

RAND MG1171/5-2.2

¹¹ Our dataset that characterizes the overall statistics on Nunn-McCurdy programs expands the dataset to include programs through June 2011 whereas the programs in Table 2.1 ended in 2009. This expansion includes an additional multiple breach program: JTRS GMR.

grams had at least one Nunn-McCurdy breach, whereas only 10 percent could be considered multiple Nunn-McCurdy breach programs.

The data in Figure 2.2 suggest that it is not the case that programs that breach once are more likely to breach again. About 40 percent of the programs breach once, and about 25 percent of the programs that breach once have further breaches. However, we must caveat this statement by noting that the sample sizes are too small to be conclusive. Thus, it is not possible to conclude that programs that breach are likely to breach again.

Phase 2: Individual Repeat Nunn-McCurdy Program Examples

We chose four programs for which to examine the breach history, challenges, and management actions in more depth. These programs are SBIRS High, C-130 AMP, JPATS, and H-1 Upgrades (4BW/4BN). Each program, with the exception of JPATS, was a multiple breach program with unique issues and challenges. JPATS was included with the other programs as a counter example; it only has had one breach.

SBIRS High

The SBIRS High program is an Air Force satellite program. According to the DAMIR:

SBIRS High is an integrated system consisting of multiple space and ground elements, with incremental deployment phasing, simultaneously satisfying requirements in the following mission areas: Missile Warning, Missile Defense, Technical Intelligence and Battlespace Awareness. The constellation architecture for SBIRS High includes Highly Elliptical Orbit (HEO) sensors and Geosynchronous Earth Orbit (GEO) satellites, in addition to the following ground elements: a Continental United States (CONUS)-based Mission Control Station and Mission Control Station Backup, overseas Relay Ground Stations, Mobile Ground Stations, and associated communication links.¹²

The program was awarded its Milestone II in October 1996. This program has the most extensive Nunn-McCurdy history of the four that we reviewed, incurring breaches in four of 13 years. In fact, the program is viewed as a “repeat offender”:

Sen. John McCain (R-AZ), the ranking member on the Senate Armed Services Committee, railed against the program’s troubled history in a speech last December [2011]. “It is worth bearing in mind that the Government Accountability Office’s latest March 9, 2011, report on major defense acquisition programs notes that SBIRS has the odious distinction of breaching the ‘Nunn-McCurdy’ law on

¹² “SBIRS HIGH Selected Acquisition Report (SAR),” Defense Acquisition Management Information Retrieval (DAMIR), December 31, 2010, p. 3.

cost growth a record four times—the most of any major weapons program. It’s a hall-of-famer,” McCain said.¹³

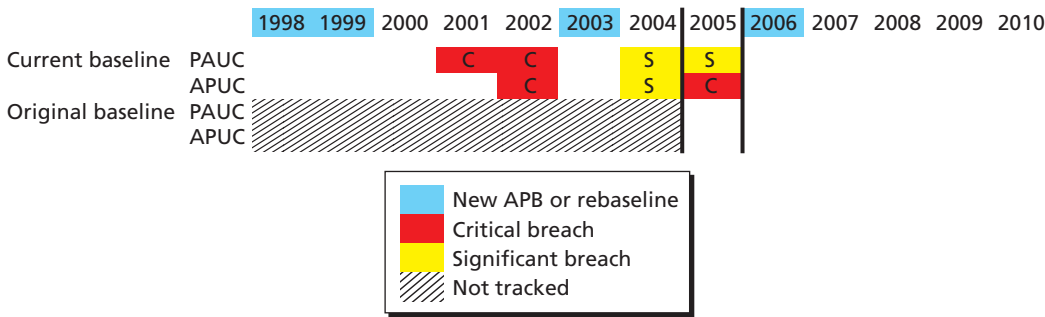
However, it is difficult to reconcile the program’s status; our counting scheme indicated that the program has two breaches. However, GAO counts four breaches for this program (see Table 2.1). Figure 2.3 illustrates both the Nunn-McCurdy breach history and the program’s new or revised APBs. SBIRS High had critical Nunn-McCurdy breaches in three years: 2001, 2002, and 2005. The program also had significant Nunn-McCurdy breaches in 2004 and 2005; but there have been no reported Nunn-McCurdy breaches since 2005. In addition to the breaches, the program has also had a series of revised APBs. After its Milestone II was awarded in October 1996, the program subsequently revised its APB in 1998, 1999, 2003, and 2006. In terms of “counting” the number of breaches, the first breach occurred in 2001 and 2002 and was resolved by the new APB in 2003. The second breach began in 2004 and ended in 2006 with another, new APB.

Figure 2.4 tracks the percentage change in the PAUC and APUC since Milestone B was awarded in 1996 using data provided in various annual and quarterly SARs. As can be seen in the chart, all four measures of unit cost grew significantly in 2002:

- The PAUC against the current baseline increased 99 percent.
- The APUC against the current baseline increased 69 percent.

Although not as pronounced as in 2002, a critical breach was also triggered in 2005 when the APUC against the current baseline grew 33 percent. It is interesting

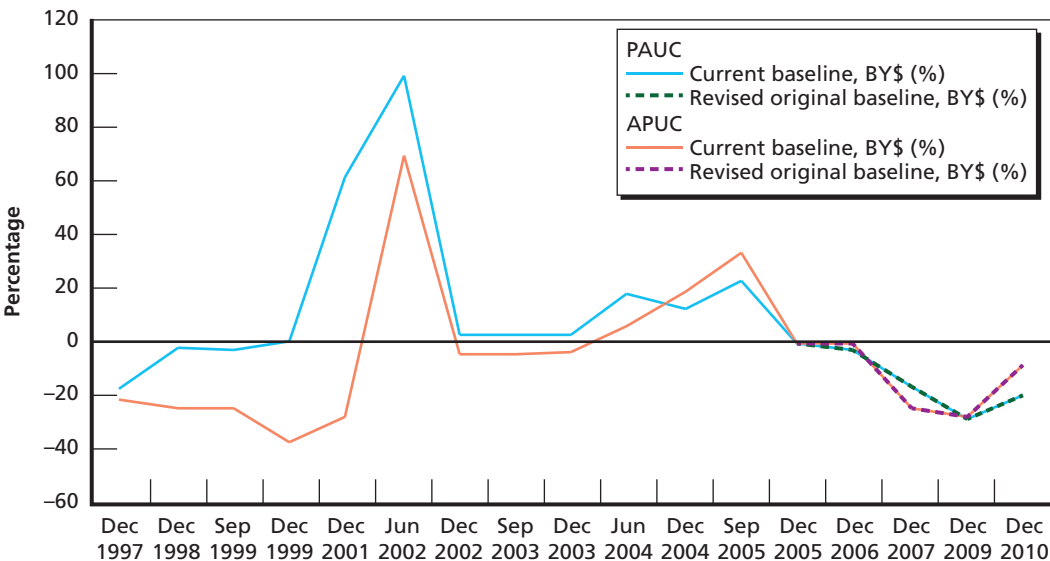
Figure 2.3
SBIRS High Nunn-McCurdy Breach History



SOURCE: “SBIRS High Selected Acquisition Reports” (1998 through 2010).
RAND MG1171/5-2.3

¹³ Christopher J. Castelli, “Pentagon Takes Key Step Toward Acquiring New SBIRS Satellites,” *InsideDefense.com*, *Inside the Pentagon*, March 15, 2012.

Figure 2.4
SBIRS High PAUC and APUC Trends



SOURCE: “SBIRS High Selected Acquisition Report” (1997 through 2010).

RAND MG1171/5-2.4

to note that this program also had two significant declines in these cost growth metrics. The APUC against the current baseline in December 1999 fell 37 percent, and in December 2009, the PAUC and APUC against the current baselines dropped 29 percent and 28 percent, respectively.

In the cost variance section, the SARs provide explanations for why costs have changed from the prior estimate to the current one. These differences are reported as individual reasons grouped by appropriation (e.g., RDT&E, procurement, military construction, operations and support) and identified with a specific cost variance category. There are seven different variance categories.¹⁴ Bolten et al.¹⁵ describe them as follows:¹⁶

1. quantity: cost variance resulting from a change in the number of end items being procured

¹⁴ William Past, “Sources of Program Cost Growth,” *Defense AT&L*, March–April 2007, pp. 24–27.

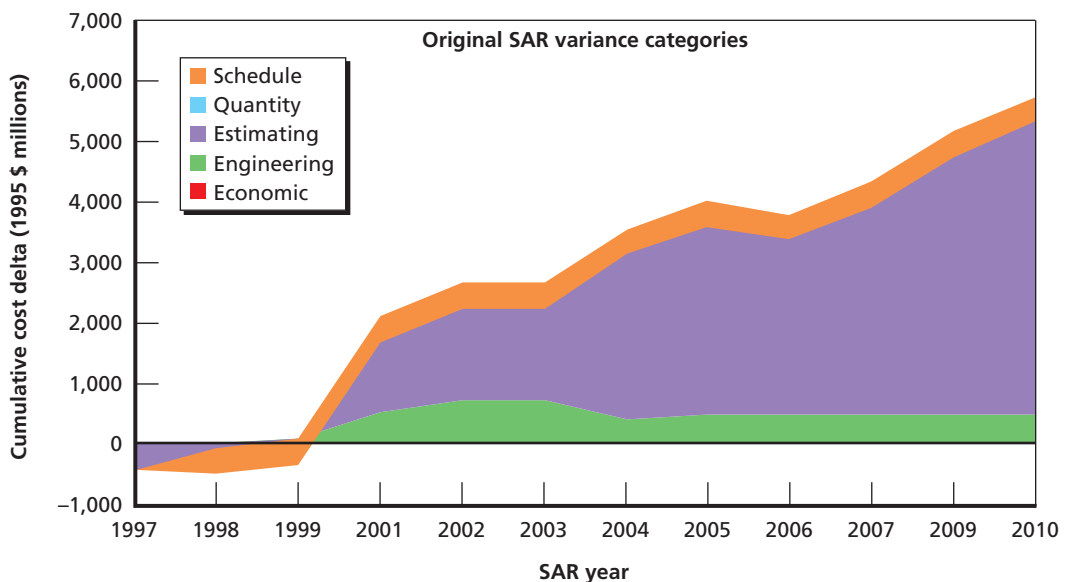
¹⁵ Joseph G. Bolten, Robert S. Leonard, Mark V. Arena, Obaid Younossi, and Jerry M. Sollinger, *Sources of Weapon System Cost Growth: Analysis of 35 Major Defense Acquisition Programs*, Santa Monica, Calif.: RAND Corporation, MG-670-AF, 2008.

¹⁶ For comprehensive definitions of the SAR cost categories, see DoD’s *Consolidated Acquisition Reporting System (CARS) Users Guide*, undated, p. 126.

2. schedule: cost variance resulting from a change in procurement or delivery schedule, completion date, or intermediate milestone for development or procurement
3. support: changes in program cost associated with training and training equipment, peculiar support equipment, data, operational site activation, and initial spares and repair parts
4. economic: cost variance resulting from price-level changes in the economy, including changes resulting from actual escalation that differs from that previously assumed and from revisions to prior assumptions of future escalation
5. engineering: cost variance resulting from an alteration in the physical or functional characteristics of a system or item delivered or under development after establishment of such characteristics
6. estimating: cost variance resulting from correction of an error in preparing the baseline cost estimate, refinement of a prior current estimate, or a change in program or cost-estimating assumptions and techniques
7. other: changes in program cost resulting from natural disasters, work stoppage, and similarly unforeseeable events not covered in other variance categories.

In Figure 2.5, we show the cumulative changes for the SBIRS program in the RDT&E appropriation. Notice that most of the growth is attributed to the “estimating

Figure 2.5
Reported Cost Variances Uninformative

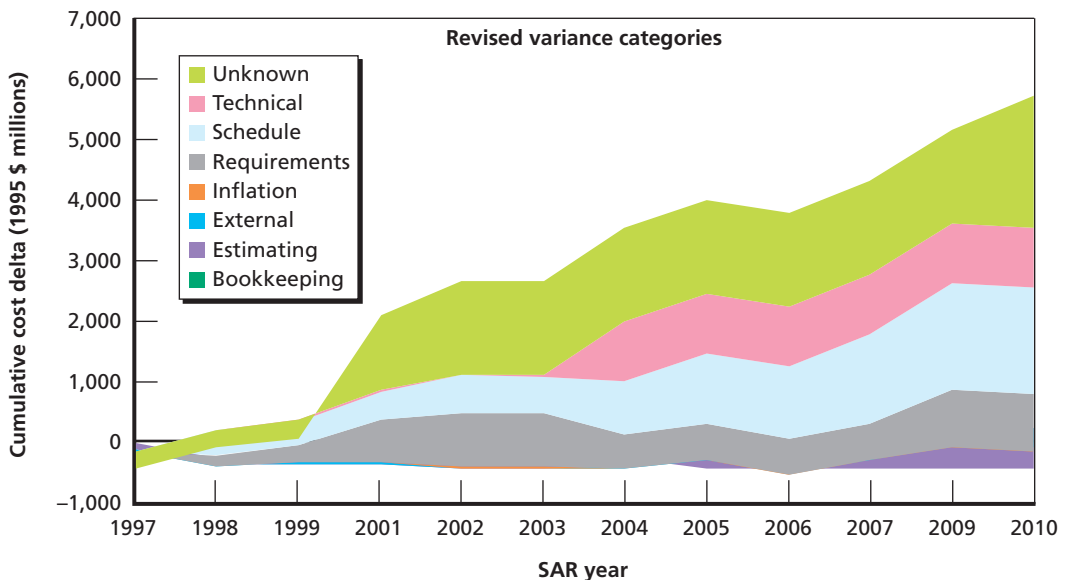


category.” But does this mean that the growth was solely due to poor estimating? To check this hypothesis, we developed our own set of variance categories:

- bookkeeping: changes that result from moving funds between one account or another
- estimating: changes resulting from revisions to the estimating assumptions or techniques
- external: changes resulting from external reasons, such as congressional action or money moved into or out of the program to fund other priorities
- inflation: changes based on inflation/escalation assumptions
- requirement: changes resulting from different adding or removing capability (additions or subtractions)
- schedule: cost changes resulting from modification to the schedule, such as delays or extending production
- technical: changes to cost resulting from technical reasons, such as redesign needed to meet original technical capability
- unknown: changes that cannot be attributed to any of the specific reasons given above.

For each variance, we assigned each of the individual explanations to a specific category using our best interpretation of the reason stated. In Figure 2.6, we show the same cumulative growth for the SBIRS RDT&E using this different categorization

Figure 2.6
Revised Cost Variance Categories Also Uninformative



of the individual cost variances. Note now that technical and schedule explanations become more prominent using these new categories. Very few issues were purely estimating, unlike the trend shown in the previous figure. More troubling is that in a large fraction of the growth, it was not possible to attribute the growth to a specific category. In the end, neither of these cost variance approaches is very illuminating. So, we did not pursue this avenue further in the analysis.

SBIRS High entered its engineering and manufacturing development (EMD) phase in 1996. In the December 1997 SAR, the program was already reporting funding and technical problems with a budget shortfall in FY 1998 that resulted from the need to accelerate some of the work to support the program's time line and because of congressionally mandated cuts. The program office chose to modify the contract to address part of the shortfall. This action delayed increment 2, all five GEO satellites, and HEO sensor delivery.

From 1997 until the first Nunn-McCurdy breach in 2001, the program experienced a series of APB breaches. The following is the explanation provided in the December 1999 SAR for the breaches:

Schedule and Cost breached due to Air Force two year delay to SBIRS High and were previously reported in both the December 31, 1998, and the September 30, 1999, SARs. On December 17, 1999, The SBIRS Program Office issued a modification that reflected the contract restructure. At the same time, an Unfinalized Contract Action option was issued for the advanced production buy for GEO 3-5 beginning in FY02. The SBIRS High data now incorporates both of these actions. As a result, the SBIRS High Acquisition Program Baseline is being updated to reflect these events.¹⁷

The December 2001 SAR reported the program's first Nunn-McCurdy breach. SBIRS High breached the critical threshold of the PAUC against the current baseline.

At Secretary of the Air Force (SECAF) direction and in concert with the prime contractor, Lockheed Martin Space Systems Company (LMSSC), an Independent Review Team (IRT) was formed to review the program and diagnose the root causes and contributing factors of the significant cost growth. Findings from the IRT are 1) the SBIRS program was too immature to enter System Design and Development; 2) the system decomposition and flow down was not well understood as the program continued to evolve; and 3) there was a significant breakdown in execution management.¹⁸

¹⁷ "SBIRS HIGH Selected Acquisition Report (SAR)," Defense Acquisition Management Information Retrieval (DAMIR), December 31, 1999, p. 8.

¹⁸ "SBIRS HIGH Selected Acquisition Report (SAR)," Defense Acquisition Management Information Retrieval (DAMIR), December 31, 2001, p. 26.

Using the results of the analysis of the breach, the program office decided to change how the program was being managed. Initially, the program was being managed using a Total System Performance Responsibility (TSPR)¹⁹ acquisition strategy at contract award, but the program office decided that the program was too complex for this strategy. The program office assumed the TSPR responsibilities after the clause was taken out of the contract. The program office also reasoned that government oversight would increase after removing TSPR from the contractor. A Program Management Board (PMB) was also established as a way to monitor changes to the program, particularly changes involving budgeting, technical, and schedule assumptions. Table 2.2 provides more detail on the challenges and actions taken to mitigate those challenges for the first Nunn-McCurdy breach. The action statements are taken directly or paraphrased from the SARs.

As the program was being restructured, the critical breach was still listed in the June 2002 SAR. By 2003, the breach was resolved and the program proceeded forward. However, in the quarterly September 2003 SAR, the program experienced a schedule APB breach as the HEO Sensor 1 Delivery and HEO Message Certification were behind schedule. This required another revised APB for the program.

In 2004, the program reported more APB breaches and a significant Nunn-McCurdy breach in the June quarterly SAR. The Nunn-McCurdy breach was a significant PAUC breach against the current baseline in addition to four APB breaches. The following is the explanation of the breaches provided in the SAR:

The current SAR reflects four additional schedule breaches resulting from the Program Office Estimate replan: Geosynchronous Earth Orbit (GEO) Satellite 1 Delivery, GEO Satellite 2 Delivery, GEO Message Certification and Mission Control Station (MCS) Increment 2 Certification. The Program Office will submit a revised APB by August 31, 2004. The revised APB will be based on the June 30, 2004, SAR cost and schedule assumptions. HEO Message Certification: This schedule event was affected by the late delivery of the HEO payloads and ground software development. GEO Message Certification/MCS Increment 2 Certification: These schedule events were affected by the late delivery of the GEO satellites and ground software development. APB Cost (RDT&E, O&M, and PAUC) and Nunn-McCurdy Unit Cost (PAUC) were breached; additional GEO 1 and 2 hardware delivery and Signal Processing Assembly software development delays have extended the procurement time, resulting in cost growth to the RDT&E, O&M and PAUC of the SBIRS program.²⁰

¹⁹ A strategy where system performance responsibility is given to the contractor and the government has reduced oversight responsibilities. See, for example, Henry P. Pandes, *A Quest for Efficiencies: Total System Performance Responsibility*, dissertation, Air Command and Staff College, Air University, April 2001.

²⁰ "SBIRS HIGH Selected Acquisition Report (SAR)," Defense Acquisition Management Information Retrieval (DAMIR), June 30, 2004, p. 6.

Table 2.2
SBIRS High First Breach Actions

Issues	Actions
Technical Risk and Maturity Area	
SBIRS program was too immature to enter system design and development (SDD)	Institute independent risk assessment of programs entering design and development.
Scope and Requirements Area	
The system decomposition and flow down was not well understood as the program continued to evolve	Major Command should be responsible for the detailed description of the expectations associated with each of the top-level requirements and assist the developer in producing a Technical Requirements Document.
Unstable requirements baseline	Work towards a final design review of the system in order to close out the liens from the Critical Design Review (CDR) and to ensure the maturity of the program to proceed further.
	Established a flag-level executive committee consisting of acquisition and operational expertise from the government and contractor, which has oversight of execution and of requirements flow management. The executive committee has the authority to adjudicate cost, schedule, and performance issues associated with requirements trades and includes all mission area stakeholders.
	Program restructured to an evolutionary block modification strategy that phases in prioritized requirements in a well-defined manner, controlled through the executive committee process.
	Have warfighters assess operational risks and prioritize requirements.
	Content baseline has been put under program office management control.
Development and Acquisition Strategy Area	
Software development strategy too complex	Implementation of a lower risk ground software approach that breaks up a single large development and transition to operations into multiple block deliveries in concert with mission needs and an achievable schedule (spiral approach).
Contract strategy (TSPR) inappropriate for level of complexity for program	Removed the TSPR clause from the contract. The program office resumed leadership of functions that had been relinquished to the contractor under TSPR.

Table 2.2 (Continued)

Issues	Actions
Performance Management Area	
Poor management performance	<p>SBIRS management has been strengthened (contractor and government).</p> <p>System engineering resources at the contractor, as well as within the government program office, have been significantly increased.</p> <p>Additional cost control measures include augmenting the Contract Funds Status Report with a detailed report of monthly budget, forecast and expenditure per product, Integrated Product Team, and total program.</p> <p>The SPO is implementing an improved Earned Value Management (EVM) process, combining traditional EVM metrics with Defense Contract Management Agency (DCMA), contractor, project officer, engineer and cost analyst assessments.</p> <p>Control of a disciplined process is being established. This includes periodic independent reviews, annual estimate at completion updates, a revised award fee structure, and new, meaningful metrics that measure program executability.</p>
Cost Estimating Area	
High unit cost growth	<p>Revised estimating methodology (vague).</p> <p>Additional cost control measures include augmenting the Contract Funds Status Report with a detailed report of monthly budget, forecast and expenditure per product, IPT, and total program.</p>
Schedule Area	
Schedule slip	<p>The newly implemented PMB acts as the decision gate and authority to approve content and disposition of cost and schedule variances. This process will help to contain requirements and content growth.</p>

SOURCES: “SBIRS HIGH Selected Acquisition Reports” and Acquisition Decision Memoranda.

The 2004 problems were not fully rectified. In 2005, the program experienced another critical Nunn-McCurdy APUC breach against the current baseline and a significant Nunn-McCurdy PAUC breach against the current baseline. The PAUC increase was attributed to several factors associated with the development effort and future production satellites (GEO 3-5). The program also experienced a growth in the PAUC as a result of manufacturing, schedule, and risk issues with the EMD contract. Schedule extensions as the result of manufacturing problems and insufficient forecasts were also contributors to the breaches. The problem took the following additional measures to control cost:

Each month, the EVM System (EVMS) information is reviewed and analyzed by both technical and EVM analysts in the program office. Results are briefed to the Segment Program Managers and SPD, and reported in the Monthly Acquisition Report and the Defense Acquisition Executive Summary. The contractor team also has weekly IPT/Segment status reviews and monthly PMR and EVM reviews. The weekly IPT/Segment meetings focus on current issues, schedule and cost performance, head count data, and business risks and opportunities. The monthly PMR addresses EVM data, schedule performance and technical issues. The monthly EVM meeting addresses the earned value performance for the month, which includes Schedule Performance Index and Cost Performance Index data, variance explanations and corrective actions.²¹

Table 2.3 provides additional details on the challenges faced by the SBIRS High program after the second set of Nunn-McCurdy breaches (actions are quotes or paraphrases from the SARs).

After the 2005 Nunn-McCurdy breach, no additional Nunn-McCurdy breaches have occurred for the program; however, the program had APB schedule, RDT&E cost, and procurement cost breaches in both 2009 and 2010. The program office attributed the schedule breach to technical issues with the flight software system (FSS) and other hardware issues that caused the program to change the delivery dates on the GEO Satellite 1 and 2. There was also a delay in the Mission Control Station (MCS) Increment 2 Certification. APB cost breaches are attributed to the addition of GEO Satellite 4 to the baseline program in the FY 2009 President's budget (PB), and funding for GEO Satellite 5 and 6 was also added to the program's budget in the FY 2011 PB. "The cost deviation against RDT&E appropriation is due to the additional costs required to complete the SBIRS EMD program as a result of schedule delays, as well as the additional costs required to implement the revised SBIRS ground delivery strategy."²²

Key Takeaways from SBIRS Review

Two factors drove the repeated breaches in the SBIRS High program, and they took years to fix:

- a lack of technical maturity throughout the program and related schedule issues
- an ineffective acquisition strategy (TSPR) that led to significant problems in requirements definition and stability.

²¹ "SBIRS HIGH Selected Acquisition Report (SAR)," Defense Acquisition Management Information Retrieval (DAMIR), September 30, 2005, p. 27.

²² "SBIRS HIGH Selected Acquisition Report (SAR)," Defense Acquisition Management Information Retrieval (DAMIR), December 31, 2010, p. 6.

Table 2.3
SBIRS High Second Breach Actions

Issues	Actions
Technical Risk and Maturity Area	
SBIRS program was too immature to enter SDD	<p>The risk to the “to go” program has been reduced by adding resources to the high risk elements and addressing the high risk elements earlier in the development phase.</p> <p>Addressing the key technical risks by adding earlier and more robust testing, as well as investigating parallel technology paths.</p> <p>A charter is in draft for an Independent Review Team (IRT) to assess the program performance three times a year and report to the Air Force Program Executive Officer for Space (AFPEO/Space) on progress achieved and future risks.</p> <p>Independent Program Assessment and Independent Costs Assessment to review technical and cost baselines.</p> <p>Revised Test and Evaluation Master Plan (TEMP)—testing program inadequate.</p>
Scope and Requirements Area	
	Reduced quantity of satellites.
Development and Acquisition Strategy Area	
?	Changed from block to annual buys.
Performance Management Area	
Poor performance	<p>Several significant cost control enhancements are being implemented in the program. Among these are the transformation of the contractor Program Performance Management Process (PPMP) and Program Office initiatives to increase government insight and influence, including restructuring the joint government-contractor surveillance program.</p> <p>Increased emphasis on business operations, predictive metrics and trending.</p> <p>Program office scheduling group and contractor team have developed the Unified Program Plan (UPP) to document and capture interdependencies, government functions, and other items not previously included in the SBIRS Integrated Master Schedule (IMS).</p> <p>Program Office is taking aggressive action to increase technical and managerial skills through increased training, as well as acquiring additional senior level staff. (Moving People to contractor site, increased oversight of production, etc.).</p>

Table 2.3 (Continued)

Issues	Actions
Cost Estimating Area	
Cost growth	<p>Several significant cost control enhancements are being implemented in the program. Among these are the transformation of the contractor Program Performance Management Process (PPMP) and Program Office initiatives to increase government insight and influence, including restructuring the joint government-contractor surveillance program.</p> <p>Unspecified revisions to the estimate.</p> <p>Independent Program Assessment and Independent Costs Assessment to review technical and cost baselines.</p> <p>The program office is continuing to work with the Air Force Cost Analysis Agency to develop an Independent Cost Model for SBIRS. The Engineering and Manufacturing Development Cost Model was validated at system and subsystem levels in December 2005. Full model estimating capabilities will be complete in January 2006.</p>
Scheduling Area	
Schedule slip	<p>System Program Director established an organic, independent scheduling analysis function within the SPO. Its mission is to analyze the contractor's program schedule, assess credibility and completeness, identify missing or improper linkages, and provide periodic reports to the senior program office staff.</p>
Externally directed production schedule delays caused an increase in parts obsolescence and extended SPO support.	<p>Second, a new cost estimate was developed to mitigate the parts obsolescence/parts redesign risk associated with the gap between GEO 2 and GEO 3.</p>

SOURCES: "SBIRS HIGH Selected Acquisition Reports" and Acquisition Decision Memoranda.

The program office focused on controlling the problems initially through such practices as better earned value management (EVM) assessments. However, beyond the technical issues, the program also experienced quantity instability that was imposed on the program by both the Air Force and the Office of the Secretary of Defense (OSD), leading to even greater instability. Also cited were multiple budgeting changes from congressional and OSD oversight.

C-130 Avionics Modernization Program

The C-130 AMP is also an Air Force program. The system “consolidates and installs the mandated Air Force Navigation/Safety modifications, the Communications Navigation Surveillance/Air Traffic Management (CNS/ATM) capabilities, and the C-130 Broad Area Review requirements on 221 of the Air Force’s Combat Delivery C-130s. These mandated modifications are incorporated with various other reliability, maintainability, and sustainability upgrades to include installation of fleetwide radars, air-crew displays, dual autopilots, dual flight management systems and HF/UHF/VHF

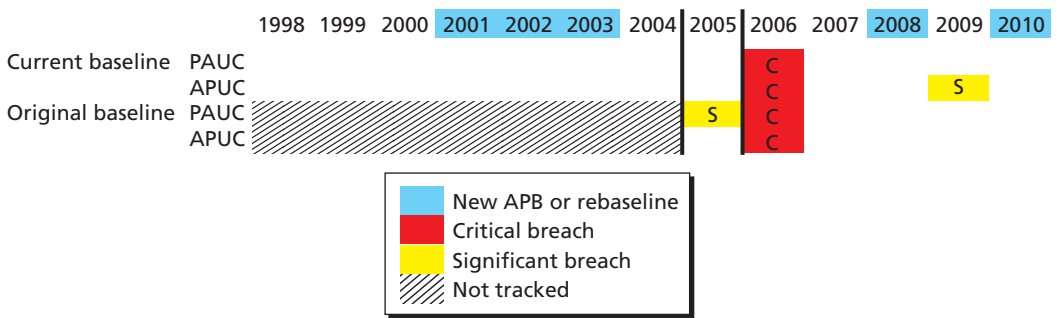
radios/data links. AMP will allow this fleet complete access to the CNS/ATM-mandated national and international air space for the foreseeable future.”²³ C-130 AMP was awarded its Milestone C in June 2010; however, the FY 2013 PB recommended its cancelation.

The C-130 AMP experienced multiple Nunn-McCurdy breaches because it reported two unrelated Nunn-McCurdy breaches. As can be seen in Figure 2.7, the first was a significant breach in 2005 that evolved into a critical Nunn-McCurdy breach of both the APUC and PAUC against both the current and original baselines in 2006. This breach was unrelated to the change in Nunn-McCurdy legislation in 2006 because the program was undergoing several issues outside the legislative change in 2006. The second was another significant Nunn-McCurdy breach of the APUC against the current baseline in 2009. The program also had four revised APBs after Milestone B in 2001.²⁴

Figure 2.8 tracks the program’s percentage change in the PAUC and APUC against original and current baselines since Milestone B was awarded in 2001 through December 2010 using data provided in various annual and quarterly SARs. As can be seen in the chart, all four measures of unit cost grew significantly in 2006:

- The PAUC against the current baseline increased 116 percent,
- The APUC against the current baseline increased 98 percent.
- The PAUC against the original baseline increased 169, and
- The APUC against the original baseline increased 120 percent.

Figure 2.7
C-130 AMP Nunn-McCurdy Breach History

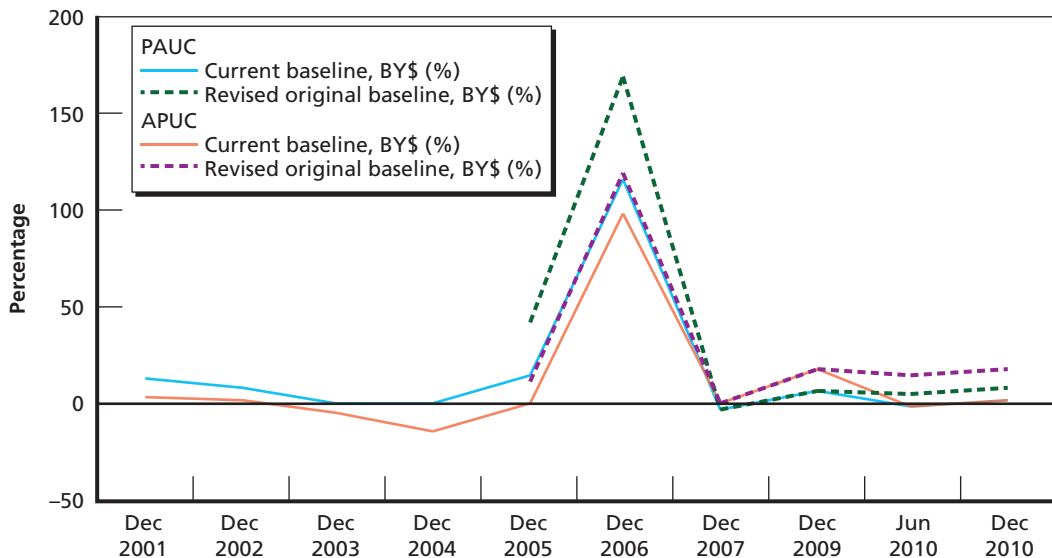


SOURCE: “C-130 AMP Selected Acquisition Reports” (1998 through 2010).
RAND MG1171/5-2.7

²³ “C-130 AMP Selected Acquisition Report (SAR),” Defense Acquisition Management Information Retrieval (DAMIR), December 31, 2010, p. 3.

²⁴ The Under Secretary of Defense (Acquisition, Technology, and Logistics) USD (AT&L) approved the program’s Milestone B for entry into SDD on July 27, 2001, according to the December 2001 SAR.

Figure 2.8
C-130 AMP PAUC and APUC Trends



SOURCE: "C-130 AMP Selected Acquisition Reports" (2001 through 2010).

RAND MG117115-3.8

After Milestone B in 2001, the ACAT 1C program immediately experienced some funding issues, technical difficulty, and cost growth in the RDT&E portion of the program. All these issues persisted throughout the development phase.

In 2001, the program office reported that there was not enough funding to meet the training system requirements in the C-130 AMP ORD. The program also reported two APB breaches in the December 2001 SAR: an RDT&E breach and a PAUC APB breach signaling some difficulties with cost control. The program also recognized that it would not be able to meet the 2005 Global Air Traffic Management requirement. A reason given for the delay was that only a limited number of aircraft could be modified simultaneously.

The program provided some explanation for the growing cost and schedule problems in the December 2002 SAR:

As a result of funding reductions in FY03 and FY04, C-130 AMP has had to slow down the ramp up of developmental activities. This slow down has resulted in a change to APB milestone dates and an increase in the cost of the program. An Engineering Change Proposal (ECP) replan is currently being evaluated and a revised APB is being staffed to reflect the proposed milestone dates. . . . In addition to the schedule breach we have an 11 percent cost increase in the RDT&E appropriation due to the additional cost to AMP associated with the stretchout of the program and the acceleration of the Common Avionics Architecture for Pen-

etration (CAAP) portion of the C-130 AMP program. The cost increases to the RDT&E line result in an APB cost breach to RDT&E and Program Acquisition Unit Cost. A Program Deviation Report (PDR) is being staffed and coordinated for both the schedule and cost breaches.²⁵

The program did not report any breaches in 2003; however, the program office once again warned about growing cost problems in the out-years that were discussed in an independent cost estimate (ICE). The ICE pointed out that the introduction of new requirements, changes in the cost estimating methodology, and projected increased depot labor rates for AMP kit installation mainly drove the cost growth. The result of cost increases in 2001, 2002, and 2003 was three new APBs, which were presented in each of these years.

The C-130 AMP program's cost growth after Milestone B breached the Nunn-McCurdy significant PAUC unit cost threshold against the original baseline when the Nunn-McCurdy legislation was amended to include reporting both the PAUC and APUC against the original baseline. The program reported a quantity reduction from 519 to 434 and a loss of funding.²⁶ The quantity reduction was due to the Air Mobility Command's decision to retire C-130E aircraft. The problem also had a mix of other issues that created instability as indicated below:

The ongoing issues stemming from funding challenges, protests and contractor overruns all factor into the current estimate activity and efforts supporting the program replan. Protest decisions have changed acquisition strategy regarding full-rate production competition and preliminary estimates reflect these costs as well. Complexities encountered during initial trial modifications, and supplier delivery delays have also contributed to contract cost overruns.²⁷

In 2006, the program faced further instability as the program breached all four Nunn-McCurdy unit cost thresholds at the critical level. The breaches can be attributed in part to another decrease in quantity from 434 to 268 as a result of a loss of U.S. Special Operations Command (USSOCOM) funding, restructure actions to realign the program budget, and increased production costs.

In June 2007, the USD (AT&L) certified the C-130 AMP after its critical Nunn-McCurdy breach. Some of the stipulations of the certification included those listed below:

- The program was transferred from ACAT 1C to 1D status making the USD (AT&L) the Acquisition Executive over the program.

²⁵ "C-130 AMP Selected Acquisition Report (SAR)," December 2002, p. 5.

²⁶ "C-130 AMP Selected Acquisition Report (SAR)," December 2005, p. 6.

²⁷ "C-130 AMP Selected Acquisition Report (SAR)," December 2005, p. 24.

- The quantity of aircraft was reduced to 222, which included C-130 H2, H2.5 and H3 Mission Design Series aircraft.
- The program was supposed to be funded to the OSD Cost Analysis Improvement Group (CAIG) estimate with reprogramming from procurement to RDT&E.

The certification also called for reworking the acquisition strategy and APB and for review of EVM. In 2007, the program worked toward Milestone C and low-rate initial production (LRIP) using an “aggressive” schedule that was outlined by the USD (AT&L).

Even with the rebaselining of the program only a couple of years before 2009, the program once again breached a Nunn-McCurdy threshold with APB breaches in schedule, procurement, and APUC. The Nunn-McCurdy breach was a significant APUC breach against the current baseline. The cause of these breaches was provided in the December 2009 SAR:

For Schedule breach, Milestone C Defense Acquisition Board (DAB) approval slipped from June 2008 to March 2010, causing a breach to the APB. Further refinement of production acquisition strategy and program costs was required prior to granting full Milestone C DAB approval. The current estimate for Milestone C DAB is March 2010. An updated Acquisition Program Baseline (APB) will follow. For Procurement and Average Procurement Unit Cost (APUC), the Cost Assessment and Program Evaluation (CAPE) estimate significantly exceeds the APB threshold. Contributors to the increase include Spares and Training Systems estimates, Milestone C schedule delays, and loss of FY 2010 procurement funding due to the Milestone C slip.²⁸

After the December 2009 breach, The Air Force wanted to cancel the program; however, Congress wanted it to continue. After a couple of years of debate, the program was recommended for cancellation in the FY 2013 budget request.

Table 2.4 provides the specific challenges and actions taken to mitigate the challenges since Milestone B. The shaded rows represent significant actions taken at the second breach.

Key Takeaways from C-130 AMP Review

The C-130 AMP program was beset by both significant quantity cuts as the program lost support and congressional cuts to funding throughout its RDT&E phase. In addition, a contract protest was the result of acquisition irregularities and led to a major acquisition strategy change—from sole source to competitive production late in development. Finally, technical issues surfaced late into design in which the retrofits were more complicated than anticipated and led to cost and schedule delays.

²⁸ “C-130 AMP Selected Acquisition Report (SAR),” December 2009, p. 5.

Table 2.4
C-130 AMP SAR Issues

Issues	Actions
Technical Risk and Maturity Area	
Technical complexity and variation of individual aircraft higher than thought	Redesign wire harness
Immature technical baseline	Program restructuring: review and restructuring delayed LRIP decision; Milestone C Defense Acquisition Board (DAB) approval slipped from June 2008 to March 2010
Scope and Requirements Area	
Unstable partnerships	USSOCOM and Sweden buy into program; rescission by USSOCOM in FY 2007 (partial in FY 2006) and Sweden in FY 2010
	Acceleration of Common Avionics Architecture Program (CAAP) for USSOCOM
Development and Acquisition Strategy Area	
GAO review after protests as a result of a criminal investigation	Change to strategy from sole source to competed installation kits—meant extending schedule for contractor acculturation (change full rate production (FRP) to open competition; added source familiarization plan). GAO imposed this change.
Performance Management Area	
Initially funded as an ACAT 1C	Changed to ACAT 1D after initial breach.
Cost Estimating Area	
Unstable costs	Develop service cost position (started in FY 2005 but not really complete until FY 2006); later, OSD pushed to use CAIG estimate after first breach (FY 2008); at second breach, program was funded to CAPE estimate. A program replanning was in the works that was designed to reconcile remaining development with funding. Rebaselined in FY 2006. Boeing did not commit to out-year pricing.
Revised cost methodologies	December 2003: The C-130 AMP began an ICE; December 2004: The C-130 AMP (as of the December 2010 SAR) is currently developing a service cost position (SCP) in conjunction with the Air Force Cost Analysis Agency to update development and production cost estimates. Preliminary SCP findings are projecting increases to program cost in FY 2007 and beyond as a result of forecasted increases in production rates, depot installation costs, and potential risks in development test.
Funding Area	
Unstable funding	Funding reductions in FY 2003 and FY 2004 (December 2002 SAR); SDD, LRIP, and production readiness review (PRR) were delayed two years as a result.
Congressional actions	Zeroed funding for FY 2010 in FY 2009.
Training line under-funded at Milestone B	Transfer of training funds to RDT&E (FY 2005) "Zero Based Transfer"

Table 2.4 (Continued)

Issues	Actions
Schedule Area	
Availability of aircraft	Stretch out of production schedule.

SOURCES: “C-130 AMP Selected Acquisition Reports” and Acquisition Decision Memoranda.

H-1 Upgrades (4BW/4BN)

The H-1 Upgrades program is a U.S. Marine Corps (Navy) midlife upgrade to the AH-1W attack helicopter and the UH-1N utility helicopter.

The mission of the AH-1Z attack helicopter is to provide rotary wing close air support, anti-armor, armed escort, armed/visual reconnaissance and fire support coordination capabilities under day/night and adverse weather conditions for the United States Marine Corps (USMC). The mission of the UH-1Y utility helicopter is to provide command, control and assault support under day/night and adverse weather conditions. Both the AH-1Z and UH-1Y aircraft incorporate state of the art designs, which serve to improve capability, lethality and survivability. Major modifications include a new four-bladed rotor system with semi-automatic blade fold of the new composite rotor blades, new performance matched transmissions, a new four-bladed tail rotor and drive system, upgraded landing gear, and pylon structural modifications. The H-1 Upgrades aircraft have increased maneuverability, speed, and payload capability. Both aircraft have fully integrated common cockpits/avionics that reduce operator workload and improve situational awareness, thus increasing safety.²⁹

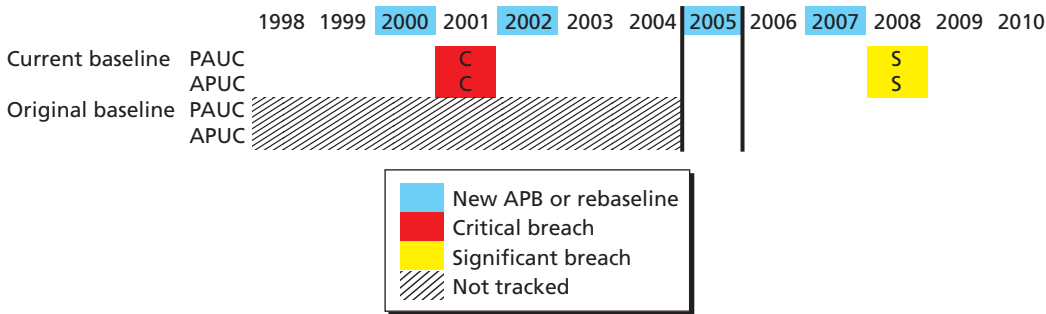
The program was awarded its Milestone C in September 2008, 12 years after it was awarded its Milestone II in 1996.

The H-1 Upgrades program is also a repeat Nunn-McCurdy breach program (see Figure 2.9). It first experienced a critical Nunn-McCurdy breach in 2001. At that time, the program had a breach against the current baseline for both the PAUC and APUC. However, it did not breach again until 2008, when the program experienced a significant PAUC/APUC unit cost growth breach against the current baseline. In addition to the breaches, the program has revised its APB four times from 1998 through 2010. It is interesting to note that the program has never experienced a Nunn-McCurdy breach against its original/revised original baseline.

Figure 2.10 tracks the program’s percentage change in the PAUC and APUC since Milestone B was awarded in 1996 using data provided in various annual and quarterly SARs. As can be seen in the figure, the program experienced its largest cost growth in 2001:

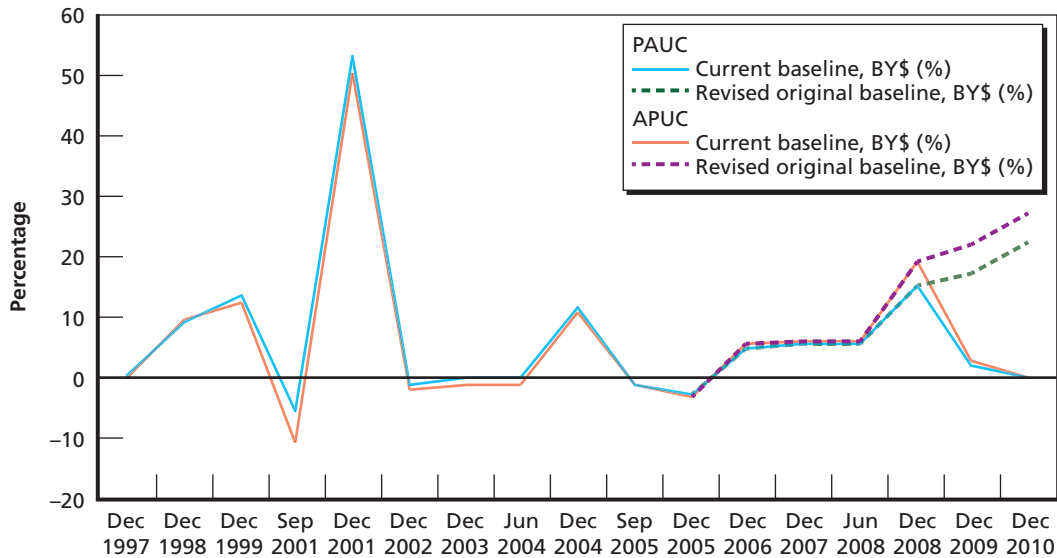
²⁹ “H-1 UPGRADES (4BW/4BN) Selected Acquisition Report (SAR),” Defense Acquisition Management Information Retrieval (DAMIR), December 31, 2010, p. 3.

Figure 2.9
H1 Upgrades Nunn-McCurdy Breach History



SOURCE: "H1 Upgrades Selected Acquisition Reports" (1998 through 2010).
RAND MG1171/5-2.9

Figure 2.10
H-1 Upgrades PAUC and APUC Trends



SOURCE: "SH1 Upgrades Selected Acquisition Reports" (1998 through 2010).
RAND MG1171/5-2.10

- The PAUC against the current baseline increased 53 percent,
- The APUC against the current baseline increased 50 percent.

The program has also had some volatility in its unit cost growth metrics over time. There are other notable peaks:

- In 1999, the PAUC grew 14 percent and the APUC grew nearly 13 percent against the current baseline.
- In 2004, the PAUC grew 12 percent and the APUC grew nearly 11 percent against the current baseline.
- In 2010, the PAUC grew 22 percent and the APUC grew nearly 27 percent against the revised original baseline.

The H1 Upgrades program was approved entry into EMD in 1996. As reported in SARs from 1997 through 2001, the program experienced a series of APB breaches signaling multiple problems that the program was experiencing during its early EMD phase primarily in regard to schedule and cost:

- December 1997 SAR: schedule and performance breaches
- December 1998 SAR: schedule breach
- December 1999 SAR: schedule, RDTE, procurement, PAUC, and APUC breaches
- September 2001 SAR: schedule and RDTE breaches.

The program reported a \$58.8 million EMD program shortfall in 1999, which required that the program office pursue funding sources for the estimate at completion (EAC) shortfall in FY 2000 and FY 2001. The program used above threshold reprogramming (ATR) and the Navy's acquisition stability reserve (ASR) fund to mitigate the shortfall along with cost-reduction initiatives. The program also reported the APB breaches for RDT&E and procurement funding. The program office said that the reasons for these breaches were based on the following:

1) Previously approved program changes such as the UH-1Y common cockpit; crashworthy AH-1Z crew seats; ground proximity warning system (GPWS); and Integrated Mechanical Diagnostic development and production. 2) Estimate at Completion (EAC) growth caused by increased contractor rates, less reused aircraft structure (than estimated), and underfunded logistics elements. A revised Acquisition Program Baseline is in process to support the new Acquisition Strategy and cost increases.³⁰

The schedule delays worsened after 1999, which forced the program to report delays of more than six months in a September 2001 quarterly SAR.³¹ The program office decided on a program restructure that would address both schedule and cost overruns. The new baseline also added "additional time for identified technical, test, and logistics risk mitigation plans prior to Operational Evaluation (OPEVAL), and

³⁰ "H-1 UPGRADES (4BW/4BN) Selected Acquisition Report (SAR)," December 30, 2001, p. 5.

³¹ This problem was also likely in 2000, but no SARs were published in 2000.

adds additional government support to recover decrements in prior fiscal years.”³² At the time, the program office warned that the program restructure would result in a significant increase in both the PAUC and APUC, shown by detailed reviews of costs by the contractor and Naval Air Systems Command (NAVAIR). This report in September 2001 came only a couple of months before the program reported its critical Nunn-McCurdy breach of both the PAUC and APUC against the current baseline.

The program office submitted its Program Deviation Report (PDR) in October 2001 as a result of the above RDT&E cost and schedule breaches. At the same time, Bell Helicopter Textron (BHTI) conducted an internal review because there was concern about deteriorating contractor performance. NAVAIR and the CAIG were also tasked to examine contractor performance and to provide a revised EAC. After these reviews, the H-1 Upgrades program proposed a program restructure described above.

Twenty percent of both the critical PAUC and APUC breach was attributed to EMD cost growth. The other 80 percent was the result of a production estimate update. The program office provided a breakdown in the December 2001 SAR of the more specific reasons for the breach as indicated in Table 2.5.

In an effort to control costs, the program office focused on revising the Engineering Mockup Unit (EMU), which was causing engineering drawings to be late and therefore EMD costs to rise. The program office also focused on improving forecasting and predictive change tools by improving contractor EVM tools, processes, procedures, and training. To limit production cost growth, the program office reviewed the production estimate in detail to get a more accurate estimate for budgeting. Specifically, the program office took the following measure to eliminate future schedule and cost problems:

The contractor and government have staffed a production team to analyze and implement transition to production cost control and efficiency measures. The contractor has invested in implementing Advanced Planning and Scheduling (APS) and Component and Supplier Management (CSM) programs to manage and control costs. The business case analysis for these programs includes commitments for direct material cost savings, inventory reduction, administrative and equipment utilization efficiencies as well as improvements in manufacturing and design productivity. The revised EMD acquisition strategy includes increased contract cost control measures. The government is currently negotiating an EMD contract modification that includes a production price commitment curve for the first two LRIP lots. In addition, the revised acquisition strategy includes an EMD performance based incentive structure if the contractor achieves predetermined scheduled or performance milestone events and EVM performance goals to further control costs.³³

³² “H-1 UPGRADES (4BW/4BN) Selected Acquisition Report (SAR),” December 2001, p. 4.

³³ “H-1 UPGRADES (4BW/4BN) Selected Acquisition Report (SAR),” December 31, 2001, p. 21.

Table 2.5**Reasons for the H-1 Upgrades 2001 Critical PAUC/APUC Breach Against the Current Baseline**

PAUC	APUC
<p>1. Material Update Based on EMD Actuals—21%: Original material estimates were developed from a parts list provided by the contractor based on similar programs. Three of the five EMD aircraft have now completed manufacturing and are in flight test (as of the 2010 SAR). The current estimate is based upon this information and comparisons with analogous systems.</p> <p>2. Learning Curve Update Based on V-22/Industry Trend—20%: Previous labor and material learning curve projections were based on AH-1W data. The learning curves have been updated based on V-22 actuals and updated industry trends that are much flatter than the previous projections.</p> <p>3. Increased Support Funds—13%: Shortly after the June 2000 APB was signed significant funding was added in the OPNAV spares requirement generation process to adequately spare to an 85% readiness goal. In addition, H-1 simulators were moved into the APN-1 program from APN-7 account. Finally, the USMC conducted a review of their Simulator Master Plan and subsequently doubled the number of simulators from seven to 14.</p> <p>4. Contractor Rate Increases—12%: The revised production estimate incorporates the current Forward Pricing Rate Agreement (FPRA) dated December 2001. The updated projections are based on lower forecasts for both commercial and military business including reduced V-22 and H-1 buys.</p> <p>5. Prime Contractor Performance—10%: The H-1 upgrades' contractor significantly underestimated the design and development tasks primarily in airframe integration and software.</p>	<p>1. Material Update Based on EMD Actuals—27%: Original material estimates were developed from a parts list provided by the contractor based on similar programs. Three of the five EMD aircraft have now completed manufacturing and are in flight test. The current estimate is based upon this information and comparisons with analogous systems.</p> <p>2. Learning Curve Update Based on V-22/Industry Trend—25%: Previous labor and material learning curve projections were based on AH-1W data. The learning curves have been updated based on V-22 actuals and updated industry trends that are much flatter than the previous projections.</p> <p>3. Increased Support Funds—17%: Shortly after the June 2000 APB was signed, significant funding was added in the OPNAV spares requirement generation process to adequately spare to an 85% readiness goal. In addition, H-1 simulators were moved into the APN-1 program from APN-7 account. Finally, the U.S. Marine Corps conducted a review of their Simulator Master Plan and subsequently doubled the number of simulators from seven to 14.</p> <p>4. Contractor Rate Increases—15%: The revised production estimate incorporates the current FPRA dated December 2001. The updated projections are based on lower forecasts for both commercial and military business including reduced V-22 and H-1 buys.</p>

SOURCE: "H-1 UPGRADES (4BW/4BN) Selected Acquisition Report (SAR)," December 2001, pp. 19–20.

After the program was certified to continue in accordance with Nunn-McCurdy law, it did not have another Nunn-McCurdy breach until 2008; however, the program continued to experience APB breaches from year to year:

- December 2004 SAR: APB schedule, RDTE, procurement, PAUC, APUC breaches
- December 2005 SAR: APB schedule breach
- December 2006 SAR: APB schedule breach
- December 2007 SAR: APB performance breach.

In June 2004, the program reported technical problems that caused a schedule delay of more than six months. According to the December 2004 SAR, “the aircraft experienced higher than expected structural strength degradation due to engine exhaust gas impinging on the tailboom and weakening the metal. In order to ensure safety margins were maintained, flight testing was temporarily suspended February 5, 2004.”³⁴ The program office modified four EMD aircraft as a temporary solution and then produced a long-term solution, although this longer-term solution required more funding. Additional time was added to the schedule because developmental testing identified other issues that included technical issues with rocket gas ingestion and weapons system integration. The sum of these issues created an RDT&E shortfall. The program reduced H-1 procurement quantities by five and converted the associated aircraft procurement funding to RDT&E as a solution.

Even with the above solutions, the program continued to have an APB schedule breach in 2005 because of the OPEVAL completion date that was not met and the AH-1Z Cruise Speed key performance parameter (KPP) that also was not met. The cruise speed KPP was modified as a result of this issue as a plan to move forward. These changes and other issues required another revised acquisition strategy and a revised APB in 2006.

In June 2008, the program experienced another Nunn-McCurdy breach. This second breach included a significant PAUC/APUC breach against the current baseline. The breach took place shortly before the program was approved for Milestone C in September 2008. The following is the program office’s explanation for the Nunn-McCurdy breach:

The H-1 Upgrades program has deviated from the approved Acquisition Program Baseline (APB). The Operational Evaluation (OPEVAL) Phase II Complete (AH-1Z) threshold date of September 2008 will not be met due to unresolved Critical Operational Issues (COIs) related to AH-1Z weapons employment. A Program Deviation Report has been submitted. A revised APB is being prepared for USD (AT&L) approval and will be presented at the September 2008 Defense Acquisition Board (DAB). As previously reported, main rotor cuff static strength limitations will preclude the UH-1Y from satisfying the Maneuverability Key Performance Parameter (KPP) requirement range of -0.5 to +2.5 (G’s).³⁵

The program office was able to satisfactorily show that the program was able to deal with the above issues, so the USD (AT&L) moved forward with Milestone C approval. Table 2.6 provides the issues that the program faced and the actions it took to continue with the program after constant schedule, contractor performance, and

³⁴ “H-1 UPGRADES (4BW/4BN) Selected Acquisition Report (SAR),” June 30, 2004, p. 4.

³⁵ “H-1 UPGRADES (4BW/4BN) Selected Acquisition Report (SAR),” Defense Acquisition Management Information Retrieval (DAMIR), June 30, 2008, p. 5.

Table 2.6
H-1 Upgrades Issues

Issues	Actions
Technical Risk and Maturity Area	
Late drawings to manufacturing	The EMU was not revised to adequately model the upgrade systems. The restructure provides funds necessary to completely revise the EMU to fully model the AH-1Z and UH-1Y upgrade systems, to ensure that the engineering analysis, manufacture effects and efficiencies are realized for any future changes.
Less reused aircraft structure (than estimated)	Modified design.
Scope and Requirements Area	
Unstable requirements	Revisions to cost estimate.
Increased readiness goal	Added additional costs for spares to achieve 85% readiness goal.
Development and Acquisition Strategy Area	
Combat losses of H-1's.	MSIII decision to build new aircraft rather than remanufacture.
Performance Management Area	
Poor contractor performance	Initiated OSD CAIG and NAVAIR independent program review. Overhauled and updated EVM though use of outside consultant. Renegotiated contract terms to incentivize control cost and schedule. Designated as a "buy-to-budget" program. NAVAIR program office and Defense Contract Management Agency (DCMA) are working with Bell Helicopter Textron Inc. to implement improved rates and overhead cost control processes.
Cost Estimating Area	
Significant contractor rates increased	Revised estimate.
Production labor & materials more than planned	Revised estimate and initiated cost reduction efforts.
Materials more expensive than estimated	Revised estimate based on EMD actuals and independent review by NAVAIR and CAIG.
Too aggressive learning curve assumed	Revised production estimate using flatter curve.
Funding Area	
Unfunded training requirements	Added funds to cover these costs.
Schedule Area	
Insufficient testing time	Schedule extended.
Insufficient logistics validation period	Schedule extended.

SOURCES: "H-1 UPGRADES Selected Acquisition Reports" and Acquisition Decision Memoranda.

technological issues. The actions taken at the second breach are shown by shaded rows. The actions taken for this program were not as clearly called out in the SARs as they were for the other programs.

Key Takeaways from H-1 Upgrades Review

The H-1 Upgrades program office faced schedule breaches and RDT&E cost growth throughout its EMD phase. One main reason was a persistent problem with contractor execution and increasing rates. The program also had late emerging technical problems caused by the recycle of designs. In addition, the cost estimating assumptions were overly optimistic causing frequent rebaselining. Finally, external events (i.e., combat losses of aircraft frames) resulted in a change to the acquisition plan whereas new airframes were purchased rather than refurbishing older ones (which were no longer available).

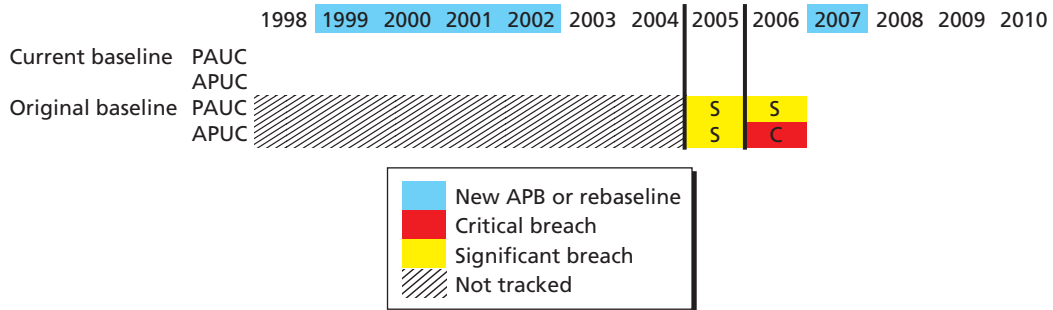
Joint Primary Aircraft Training System

JPATS is an Air Force and Navy program that is meant to “replace USAF’s T-37B aircraft, USN’s T-34C aircraft, and the associated Ground Based Training Systems (GBTS). The aircraft and GBTS are being used to train entry-level students in the fundamentals of flying so they can transition into advanced training tracks leading to rated qualification. The program represents a systems approach to aviator training requiring the purchase of air vehicles (747 production units), aircrew training devices (126), associated ground based training devices, an integrated training information management system (TIMS), instructional courseware, as well as the entire logistics and sustainment of the training system which includes contractor logistics support (CLS).”³⁶ The program was awarded its Milestone II in August 1995 and its Milestone III in December 2001.

Unlike the previous programs discussed in this section, JPATS is not a multiple Nunn-McCurdy breach program. As shown in Figure 2.11, the program reported Nunn-McCurdy breaches in both 2005 and 2006; however, the breaches in 2005 were not resolved administratively by 2006, so we consider these as only one breach. This trend frequently happens when breaches are reported because it takes a considerable time for programs to go through the Nunn-McCurdy process and for revisions to be made to the program’s path so that future cost growth can be avoided. This program may also have been caught up in the change in Nunn-McCurdy reporting requirements during the time period of the breach. This change, which included additional reporting of unit cost growth against the original baseline, negatively affected programs that would not have otherwise breached. We also cannot rule out the possibility that the program was avoiding breaching by rebaselining four times from 1998

³⁶ “JPATS Selected Acquisition Report (SAR),” Defense Acquisition Management Information Retrieval (DAMIR), December 31, 2010, p. 3.

Figure 2.11
JPATS Nunn-McCurdy Breach History



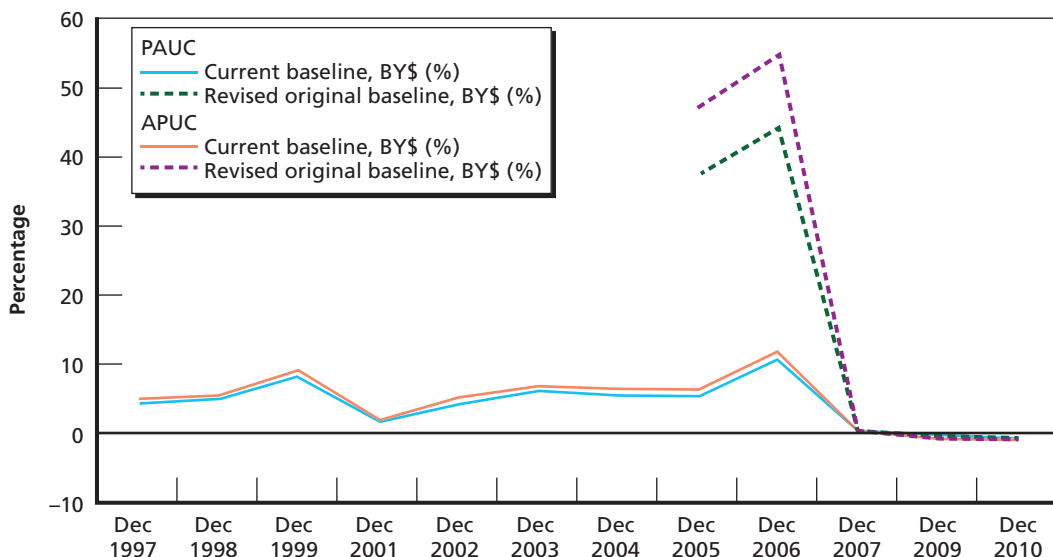
SOURCE: "JPATS Selected Acquisition Reports" (1998 through 2010).

RAND MG1171/5-2.11

through 2004. Part of the rationale for the change in legislation in 2006 was to shed light on cost growth that may not have been as visible because of frequent rebaselining.

Figure 2.12 tracks the program's percentage change in the PAUC and APUC against both the current and original baselines as available since December 1997. As can be seen in the chart, the PAUC and APUC have been relatively steady over time

Figure 2.12
JPATS PAUC and APUC History



SOURCE: "JPATS Selected Acquisition Reports" (1997 through 2010).

RAND MG1171/5-2.12

except in 2005/2006 when both rose significantly when the original baseline was introduced:

- The PAUC against the original baseline increased 44 percent; and
- The APUC against the original baseline increased 55 percent.

From 1997 to 2004, the program experienced minimal APB breaches and no Nunn-McCurdy breaches. JPATS had an APB procurement cost breach in 1998 and an APB schedule breach in 2002. It did not have any APB breaches in 2003 or 2004. Until the 2005 significant Nunn-McCurdy breach of both the APUB and PAUC against the original baseline, the program appears to have been controlling cost even with multiple instances of technical setbacks.

Difficulties experienced by the program before the 2005 breach include a delay in awarding the EMD contract in 1995 at Milestone II because two protests were filed by Rockwell and Cessna when Raytheon was awarded the contract. The GAO denied all allegations and the first production lot option was exercised in February 1996. In the next couple of years following Milestone II, assembly of the first test aircraft (T-1) was behind schedule. The delay was caused by a late delivery of both the tools and computer-aided manufacturing software. There was also an industrywide shortage of experienced workers who were working on this test aircraft. These complications caused a seven-week delay in the T-1 aircraft.

In FY 1999, the program's funding level would not permit the execution of the FY 1999 contract options as planned to install TIMS at all seven Air Education and Training Command (AETC) pilot training bases. The funding complications in FY 1999 caused some additional schedule delays for the program along with the fact that the TIMS system was difficult to develop.

In January 1999, the program experienced several technical issues. The P-2 aircraft engine malfunctioned, which forced the program to ground all aircraft. In addition, in February 1999, the rear fuselage also needed structural modifications. Finally, the program experienced problems with the environmental control system, the engine's automatic airstart system, and the aircraft's empennage structure system. This combination of technical problems caused the program office to prepare a new baseline for the program in 1999.

During 2002, the aircraft production contract was changed from award fee to a performance incentive fee structure. According to the SAR,

The reason for the change is that the old contract delivery schedule did not provide sufficient margin between aircraft availability and aircraft requirements (training and retrofit) in the December 2002 through February 2003 time frame. The SPO chose to incentivize early deliveries to ensure a sufficient margin of aircraft availability. PT-75 and on were delivered ahead of contract schedule as a direct result of this contract incentive. An additional benefit of the accelerated aircraft delivery

schedule was that a greater number of aircraft with the upgraded environmental control system (ECS) were involved in the MOT&E(S).³⁷

The program experienced more technological setbacks in both 2004 and 2005. In April 2004, the T-6A crashed, killing two instructor pilots. A detailed investigation was done to understand the cause of the crash. Then, in 2005, the Navy reported an in-flight engine failure. This led to another investigation. JPATS engineers and Pratt & Whitney concluded that all engines over 2,000 hours were at risk of turbine blade failure, forcing both the Air Force and Navy to stop using aircraft with over 2,000 flight hours and make repairs.

Also in 2005, the program had to start reporting unit cost against the program's "original" APB, i.e., the APB established at Milestone B (previously Milestone II). Because of this new requirement, the program had to report an increase in the PAUC of 37 percent and 47 percent in the APUC. The program reported the following as the causes for the breaches:

The PAUC increase from MS II to MS III was caused by an increase in cost due to foreign sales not materializing, increased material costs, flattening of the learning curve and a decrease in quantity. The PAUC increase from MS III to present is a result of increased estimate of unit flyaway cost, redetermination of lead service change cost, the decision to procure all required Navy program related spares and other minor changes in support, engineering changes and mission support. The APUC increase from MS II to MS III was caused by an increase in cost due to foreign sales not materializing, increased material costs, flattening of the learning curve and a decrease in quantity. The APUC increase from MS III to present is also due to an increased estimate of unit flyaway costs, redetermination of lead service change cost, the decision to procure all required Navy program related spares and other minor changes in support, engineering changes and mission support.³⁸

The program reported even greater percentage changes in the PAUC and APUC against the original baseline in 2006. The PAUC increased 44 percent against the original baseline and the APUC increased nearly 55 percent against the same baseline triggering a significant Nunn-McCurdy breach for the PAUC metric and a critical Nunn-McCurdy breach for the APUC metric. The program office used a similar explanation for the breaches as in 2005. Table 2.7 consolidates the various problems relevant to the breach that the program has experienced since 1997. It then provides any issues and actions taken to correct the problems moving forward.

³⁷ "JPATS Selected Acquisition Report (SAR)," December 31, 2002, p. 6.

³⁸ "JPATS Selected Acquisition Report (SAR)," Defense Acquisition Management Information Retrieval (DAMIR), December 31, 2005, p. 29.

Table 2.7
JPATS SAR Issues

Area	Issues	Actions
Technical risk and maturity	Technical problems with engine, landing gear, and airframe	Redesign of affected components
Scope and requirements		
Development and acquisition strategy	Protest on contract award	Delay of program start, but both protests were denied
	Lack of schedule incentive for contractor	Change from award to incentive fee contract
Performance management		
Cost estimating	Underestimated cost	Revised manufacturing assumptions
Funding	Navy deferred procurement in FY 2002	Increase of unit costs
Schedule	Shortage of skilled workers	Schedule delayed; contract changed to incentive fee

SOURCES: “JPATS Selected Acquisition Reports” and Acquisition Decision Memoranda.

Key Takeaways from JPATS Review

JPATS experienced numerous technical issues during production that required fixes. The program identified the causes of these issues and implemented solutions using redesign and active maintenance without causing major delays in the program’s schedule. Actions taken also minimized cost growth. Toward the end of production, the Navy decided to cut quantities by 20. This also resulted in a cut in funding by Congress in FY 2011. The program also anticipated that foreign sales would help to offset the price. These sales materialized only late in the program and did not help to reduce costs stemming from cuts to the U.S. quantities. However, the program has not experienced another Nunn-McCurdy breach because of the quantity reduction.

It is possible that this program did not experience a repeat Nunn-McCurdy breach because it was able to deal with its technological problems and was four years into production at the time of the first breach. Also, this program was one of those that seemed to breach once the Nunn-McCurdy law was changed in 2006 to require reporting against the original baseline. Had the law change not occurred, it is possible this program would not have breached even once.

Observations

The change in the Nunn-McCurdy law in 2006 profoundly affected the way breaches are reported. Before 2006, programs could rebaseline. So if the cost growth was not rapid or abrupt, breaches against the original baseline could be masked. Now, because programs report against the original baseline, many more appear to breach now than in the past. For example, Congressional Research Service noted³⁹ that 11 programs were reclassified as having breaches after the law change. Thus, it is very difficult for us to state whether breaches have become more frequent recently. The breaches are certainly recognized more often now.

Our answers to the original questions of this research follow.

Are programs that have a Nunn-McCurdy breach more likely to breach again? The evidence we have gathered does not suggest that programs that have one breach are more likely to breach again. However, our sample size is small, and the 2006 law change makes any conclusive view impossible.

What can we learn from the cost growth trends of those programs that have had multiple Nunn-McCurdy breaches? We observed that most of the programs with multiple breaches tend to have very rapid cost growth displayed in the SARs. They jump directly into a critical breach between years or rapidly move from significant to critical breach. There seems to be no advanced warning from the cost growth that indicates a potential breach. Also, the APUC and PAUC measures are highly correlated for most programs. We explored growth in the cost variance categories and did not find anything of note.

What can we learn from the management actions taken on programs with multiple breaches? It is very difficult to answer this question with the limited program information we had available. After interpreting the SARs and ADMs, we attempted to classify the major actions taken at the first breach and how they did or did not affect the second breach. We classified the actions taken at the first breach as follows (in accordance with the PARCA office recommendations):

- Did not recognize the problem—the issues that led to the second breach were not understood at the time of the initial breach.
- Recognized the problem but took no corrective action—the issue related to the second breach was identified, but no specific action was taken to prevent it.
- Recognized the problem and did not take the appropriate corrective action—the problem that led to the second breach was recognized, but the action taken did not avert it or was ineffective.

³⁹ Schwartz, 2011.

- Recognized the problem and took action, but did not fully understand implications—the issues leading to the second breach were recognized, but the full implications of the problem were not understood.
- Recognized the problem and took appropriate action.
- Issues took more time to resolve than time to rebaseline—the corrective actions were difficult to implement and the second breach occurred before the initial actions were fully implemented.

In Table 2.8, we attempt to classify the issues and categorization of the actions taken at the first breach for the four programs we explored. Again, this table is a highly speculative and subjective assessment. It is interesting to note that we found no clear-cut instances where no action was taken. For all three of the programs with multiple breaches, resolving the technical maturity issues took time and was still an issue at the second breach. For the SBIRS and H-1 Upgrades programs, there was focus on rebase-

Table 2.8
Issues Versus Actions Taken at First Breach

	SBIRS	C-130 AMP	H-1 Upgrades	JPATS
Did not recognize the problem	Schedule plan was not realistic			
Recognized the problem but took no corrective action				
Recognized the problem and did not take the appropriate corrective action or actions were ineffective	Rebaseline and improved EVM did not limit further costs growth		Rebaseline and improved EVM did not limit further costs growth	
Recognized the problem and took action, but did not fully understand implications	Change of acquisition strategy from TSPR to more government control	Increased cost and time led to quantity cuts from partners, change from sole source to competitive production also added cost		Increased cost and time led to quantity cuts from partners
Recognized the problem and took appropriate action	Insufficient technical and program manager resources	ICE needed		Restructured contract, improved technical maturity
Issues took more time to resolve than time to rebaseline	Improved technical maturity, realistic cost baseline, insufficient technical and program manager resources	Improved technical maturity	Improved technical maturity	

lining and fixing the EVM system so that it accurately reflected the program status. However, the new cost baseline was unrealistic in both cases as the technical issues and contractor performance continued to challenge both programs. Some program changes had implications that were not fully understood. The most striking of these were the two acquisition strategy changes for SBIRS High and C-130 AMP. The other noteworthy observation from the table is the vulnerability of joint or international programs to quantity cuts when costs increase—leading to the so-called “unit cost death spiral” (cost increases lead to quantity cuts, which leads to further cost increases . . . and so on).

In the discussion below, we address the last question, **are there common issues that were missed at the first breach?** In Table 2.9, we summarize the common issues observed across the four programs examined. Note that all programs had schedule and technical issues, even JPATS, which did not breach multiple times. The two characteristics common to the programs with multiple breaches were that they had significant quantity variances and immature cost estimates. It should be noted that the quantity issue is more associative than causal. Another observation that can be made from Table 2.9 is that two of the programs with multiple breaches had major changes to their acquisition strategy and direct congressional influence in the program. These observations suggest that further research could be done on a more complete set of programs looking for common characteristics and trying to quantify how they might influence the likelihood of multiple breaches. For example, further research might show whether programs with significant quantity changes are more prone to another breach or whether quantity changes are just a symptom of other program problems.

The common issues listed in Table 3.9 have some similarities to other root causes for other DoD programs identified in recent research done by RAND (for PARCA).

Table 2.9
Common Issues

Issue	SBIRS High	C-130 AMP	H1 Upgrades	JPATS
Significant quantity variances	X	X	Xa	
Major change in acquisition strategy	X	X		
Protests		X		X
Technical problems	X	X	X	X
Congressional redirection	X	X		
Cost-estimating not mature until late	X	X	X	X
Schedule delays	X	X	X	X
Joint/international		X		X

^a Combat losses of aircraft frames resulted in a change to the acquisition plan in which new airframes were purchased rather than refurbishing older ones, thus raising the cost.

Blickstein et al. summarize root causes for several programs that have had Nunn-McCurdy breaches (i.e., Joint Strike Fighter, Excalibur, Wideband Global Satellite, Longbow Apache DDG-1000, and JTRS GMR).⁴⁰ Several of the root causes identified are similar to those we have observed in this study. The common root causes are as follows:

- changes (up or down) in procurement quantities
- underestimation of costs/overoptimistic cost estimates
- immature technologies resulting in later technical problems
- ineffective contract incentives.

Conclusions

This chapter has explored three issues related to programs that have multiple Nunn-McCurdy breaches. We found that programs that breached once are not more likely to breach a second time. The 2006 change in the Nunn-McCurdy law has increased awareness of programs that breach above their initial baselines. We have found no obvious cost growth trends that would suggest that a program might breach more than once. In terms of actions taken at the first breach, those that breached more than once had technical issues that were not resolved by corrective actions taken at the first breach. Finally, we did find some common characteristics among those programs with multiple breaches. But because our sample was small, the results are not definitive, and further research might refine this view.

⁴⁰ Irv Blickstein, Michael Boito, Jeffrey A. Drezner, James Dryden, Kenneth Horn, James G. Kallimani, Martin C. Libicki, Megan McKernan, Roger C. Molander, Charles Nemfakos, Chad J. R. Ohlandt, Caroline Reilly, Rena Rudavsky, Jerry M. Sollinger, Katharine Watkins Webb, and Carolyn Wong, *Root Cause Analyses of Nunn-McCurdy Breaches, Volume 1: Zumwalt-Class Destroyer, Joint Strike Fighter, Longbow Apache, and Wideband Global Satellite*, Santa Monica, Calif.: RAND Corporation, MG-1171/1, 2011.

Nunn-McCurdy Legislation

The Nunn-McCurdy Act, whose purpose is to help control cost growth in MDAPs, requires that the DoD report unit costs for major weapons systems to Congress. This legislation was originally signed into law in the early 1980s and has undergone a variety of changes over 30 years. Nunn-McCurdy legislation established thresholds as a way of monitoring cost growth. When cost growth surpasses the thresholds established in the legislation, a process is set in motion whereby the program office and other parties in the DoD must notify Congress of the growth and reasons behind it.

Original Nunn-McCurdy Legislation

In 1981, Senator Samuel Nunn and Congressman David McCurdy introduced the Nunn-McCurdy amendment¹ to the Department of Defense Authorization Act of 1982.² The purpose of the amendment was to establish congressional oversight of defense weapon system acquisition programs that experience cost growth above limits specified in the amendment. The Nunn-McCurdy amendment defined two types of unit cost: total PAUC, which is the sum of development funding and procurement funding divided and military construction by units procured; and APUC, which is the procurement funding divided by units procured. Cost growth of a weapon system was measured by how much the unit costs in 1982 exceeded the same respective unit costs in the weapon system's SAR dated March 31, 1981. Hence, the amendment applied only to those major weapon systems with March 31, 1981, SARs.

The original amendment required that the Secretary of Defense (SECDEF) notify Congress when a major weapon system unit cost growth exceeded 15 percent. If unit cost growth exceeded 25 percent, the program was assumed terminated unless the Secretary of Defense submitted specific written certifications to Congress within 60 days of making the cost growth determination. These certifications survive in current law.

¹ The Nunn-McCurdy amendment is also known as the Nunn-McCurdy provision. See Nunn-McCurdy Amendment, Department of Defense Authorization Act, 1982, Report No. 97-311, November 3, 1981.

² Public Law 97-86, National Defense Authorization Act of 1982, December 29, 1981.

Congress made the provisions of the Nunn-McCurdy amendment permanent in the 1983 Authorization Act³ by requiring that the secretary of each military department establish a baseline description of each major weapon system acquisition program under the jurisdiction of the secretary. The baseline description was to include a baseline estimate of the program cost. The permanent Nunn-McCurdy provisions measured unit cost growth by comparing the current unit costs against the same respective unit costs in the baseline estimate. The cost thresholds for notifying Congress and for program termination presumptions in the original Nunn-McCurdy amendment remained unchanged in the 1983 Authorization Act but have subsequently changed.

Changes to Nunn-McCurdy Legislation Since 1982

Since the original Nunn-McCurdy legislation was enacted, Nunn-McCurdy legislation has evolved with significant changes to the legislation in both 2006 and 2009. Other changes were relatively minor in comparison and included changes to previously established thresholds, definitions of unit cost measures, Nunn-McCurdy process timelines/deadlines, and documentation requirements. See Figure A.1 for more details on the changes over time:

The FY 2006 National Defense Authorization Act (NDAA) (P.L. 109-163) included a major addition to the Nunn-McCurdy legislation that affected MDAPs and the management of those programs. Congress mandated that cost growth be measured against the current baseline estimate and the original baseline estimate. In fiscal year 2006:

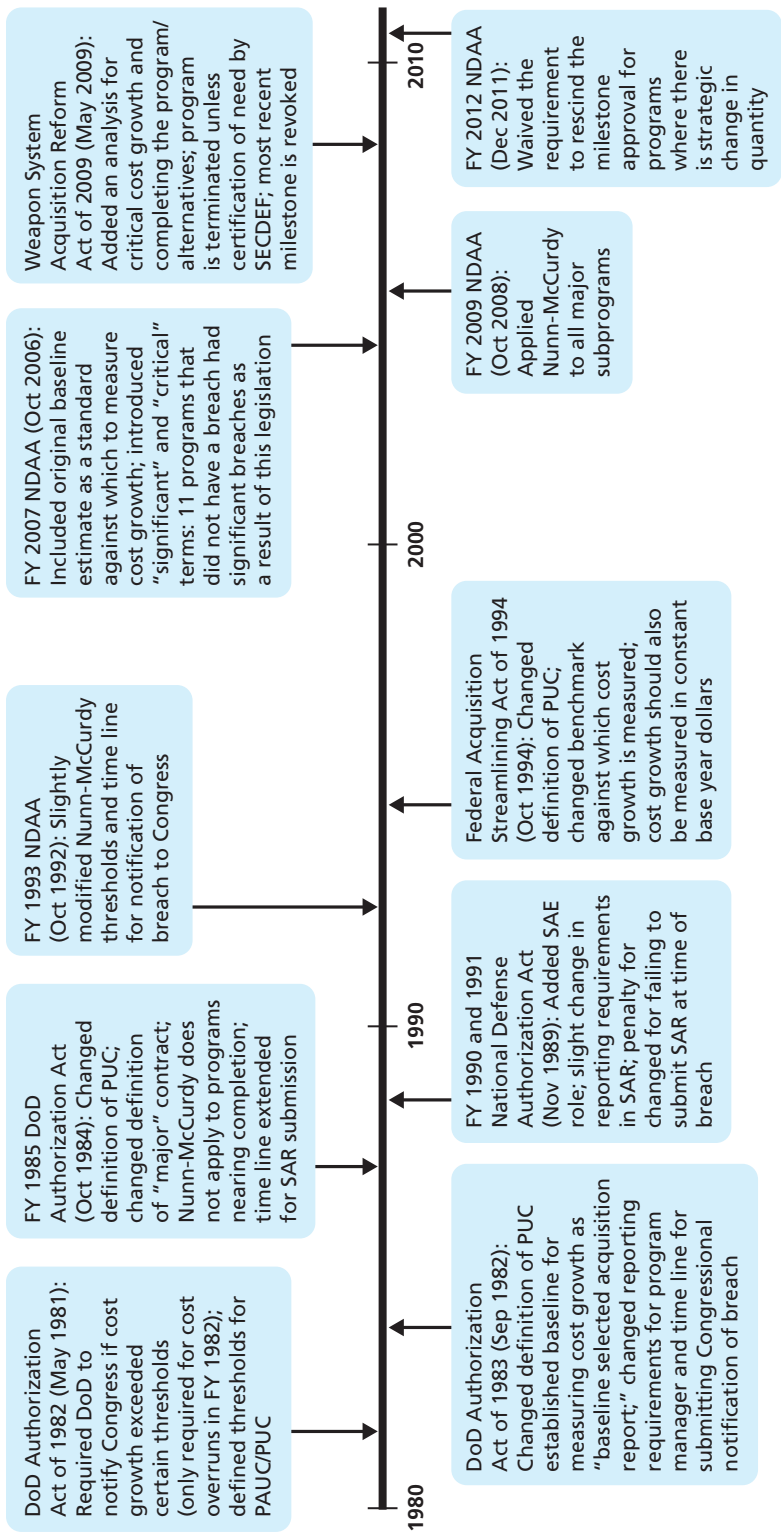
Congress added the original baseline estimate as a benchmark against which to measure cost growth. The original baseline estimate is defined as the baseline description prepared before the program enters development, or at program initiation, whichever is later, without adjustment or revision. By adding the original baseline estimate as a benchmark against which to measure cost growth, and by restricting the circumstances in which an original baseline estimate may be revised, DOD can no longer avoid Nunn-McCurdy breaches by simply revising a program's baseline estimate. While DOD acquisition policy still allows current baseline estimates to be revised, the policy was modified in 2008 to limit the circumstances under which this may be done.⁴

As a result of this legislation, more programs had Nunn-McCurdy breaches than otherwise would have been the case. "According to DOD, 11 programs that did not have a Nunn-McCurdy breach prior to the new FY2006 requirements were recatego-

³ Public Law 97-252, National Defense Authorization Act of 1983, September 8, 1982.

⁴ Government Accountability Office, 2011a, pp. 3–4.

Figure A.1
Key Events in History of Nunn-McCurdy Legislation



alized as having significant breaches as a result of the legislation's new original baseline."⁵ This change in legislation is particularly relevant to this section of the report on repeat Nunn-McCurdy programs. Some of the repeat Nunn-McCurdy breaches can be attributed in part to changes in legislation. In addition to legislative changes, the GAO also attributes some of the repeat breaches to changes in presidential administration.⁶

Approximately three years after the 2006 legislation, the Weapon System Acquisition Reform Act (WSARA) of 2009 (P.L. 111-23) was passed. WSARA revised Nunn-McCurdy laws to include a more complicated process and established a new office to examine the causes of Nunn-McCurdy breaches and related issues. Specifically, WSARA required the following for programs that the USD (AT&L) believed should not be terminated:

- Additional certification to Congress is required, stating that the program is higher priority than programs whose funding must be cut to cover the cost growth of current program.
- Revocation of most of the recent milestone approval is required and no new contracts can be awarded without new milestone approval or MDA approval.
- Analysis should be conducted to determine the root cause of cost growth.
- Program must be restructured to address root causes of cost growth.
- Failure to certify to Congress the results of the above findings results in program termination.⁷

The WSARA changes may be the most pivotal since the Nunn-McCurdy legislation was enacted in 1982. In fact, they may have been too extensive as Congress backtracked on some of the requirements from WSARA regarding Nunn-McCurdy reporting in Section 801 of Title VIII of the FY 2012 legislation because of concerns about the burden (or costs) of compliance:

The committee recommends a provision that would allow the waiver of certain requirements applicable to programs that experience critical Nunn-McCurdy breaches as a result of steep growth in unit costs, in cases where such cost growth is attributable entirely (or almost entirely) to changes in the number of units to be purchased. The provision recommended by the committee includes strict standards to ensure that all Nunn-McCurdy requirements remain applicable in any case where poor program management or performance contributes to the increase in unit costs.⁸

⁵ Schwartz, 2011, p. 10.

⁶ Government Accountability Office, 2011a, p. 2.

⁷ Schwartz, 2011, p. 10.

⁸ National Defense Authorization Act for Fiscal Year 2012, 112th Congress, 1st Session Report, June 22, 2011, p. 135.

Current Nunn-McCurdy Process

The current Nunn-McCurdy process is largely the same as the original outside the major additions in both 2006 and 2009. If a program breaches the Nunn-McCurdy thresholds, then the program undergoes considerable scrutiny by Congress and the DoD in which the program office must provide Congress with reasons for cost growth and plans for how to avoid it in the future. Currently, there are two unit cost criteria that are considered for the thresholds. The first is PAUC⁹ and the second is APUC.¹⁰ Both are required to be reported in base year dollars to take into account inflation. Both of the current estimates¹¹ of these unit costs are then compared to both the current baseline estimate¹² and to the original baseline estimate.¹³ The law requires specific actions and reporting if a program breaches the unit cost thresholds. A significant breach occurs when the current baseline estimate is breached by 15 percent or the original baseline estimate is breached by 30 percent. A critical breach occurs when the current baseline estimate is breached by 25 percent or the original baseline estimate is breached by 50 percent.

If a program has a significant Nunn-McCurdy breach, the appropriate service secretary must notify Congress within 45 days of the unit cost report. This usually takes the form of a “program deviation report.” The DoD then submits an SAR with required unit cost breach information (this may be a quarterly SAR or can be included in the annual SAR).

⁹ PAUC = [Total Development \$ + Procurement \$ + Construction \$] / Total program quantity.

¹⁰ APUC = Total Procurement \$ / Procurement quantity.

¹¹ Latest estimate of approved program.

¹² Currently approved APB.

¹³ APB approved at Milestone B or program initiation, whichever occurs later.

List of Programs with at Least One Nunn-McCurdy Breach (1997–2011)

Advanced Anti-Tank Weapon System—Medium (Javelin)
Advanced Extremely High Frequency (AEHF) Satellite
Advanced Field Artillery Tactical Data System (AFATDS)
Advanced SEAL Delivery System (ASDS)
Advanced Threat Infrared Countermeasure/Common Missile Warning System (ATIRCM/CMWS)
AH-64D LONGBOW APACHE
AH-64E Apache Remanufacture
Armed Reconnaissance Helicopter (ARH)
Army Tactical Missile System (TACMS)/BAT
B-1B Conventional Mission Upgrade Program (CMUP)
C-130 Avionics Modernization Program (AMP)
C-130J Hercules Transport Aircraft
C-27J Spartan
C-5 Reliability Enhancement and Reengineering Program (RERP)
CH-47F Improved Cargo Helicopter (CH-47F)
Chemical Demilitarization Program
Chemical Demilitarization—Assembled Chemical Weapons Alternatives (Chem Demil—ACWA)
Chemical Demilitarization—Chemical Materials Agency Newport (Chem Demil—CMA Newport)
Chemical Demilitarization—U.S. Army Chemical Materials Agency (Chem Demil—CMA)
Comanche Reconnaissance Attack Helicopter (RAH-66)
DDG 1000 Zumwalt Class Destroyer
E-2D Advanced Hawkeye (AHE)
Evolved Expendable Launch Vehicle
Expeditionary Fighting Vehicle (EFV)
F/A-18E/F Naval Strike Fighter (SUPER HORNET)

F-22 Raptor Advanced Tactical Fighter Aircraft
F-35 Joint Strike Fighter (JSF)
Family of Medium Tactical Vehicles (FMTV)
Force XXI Battle Command Brigade and Below (FBCB2)
Guided Multiple Launch Rocket System (GMLRS)
H-1 Upgrades (4BW/4BN)
Increment 1 Early-Infantry Brigade Combat Team
Joint Air-to-Surface Standoff Missile (JASSM)
Joint Land Attack Cruise Missile Defense Elevated Netted Sensor System (JLENS)
Joint Primary Aircraft Training System (JPATS)
Joint Tactical Radio System (JTRS) Ground Mobile Radio (GMR)
Land Warrior (LW)
Littoral Combat Ship (LCS)
LPD 17 San Antonio Class Amphibious Transport Dock
MH-60R Multi-Mission Helicopter
MH-60S Fleet Combat Support Helicopter
National Polar-orbiting Operational Environmental Satellite System (NPOESS)
NAVSTAR Global Positioning System
Navy Area Theater Ballistic Missile Defense (TBMD)
Remote Minehunting System
RQ-4A/B Global Hawk Unmanned Aircraft System
Sense and Destroy Armor (SADARM)
Space Based Infrared System (SBIRS) High Program
SSN 774 Virginia Class Submarine
V-22 Osprey Joint Services Advanced Vertical Lift Aircraft
Warfighter Information Network—Tactical (WIN-T)
Wideband Global SATCOM (WGS)
XM982 155mm Precision Guided Extended Range Artillery Projectile (Excalibur)

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